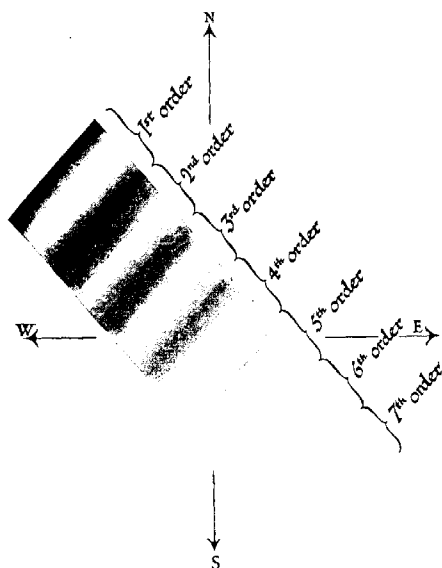# MINERALS AND THE MICROSCOPE

Newton's Scale.

The colours are seen when a wedge of quartz or gypsum is placed in an oblique position between crossed nicols.

The points of the compass illustrate the scheme adopted in order to indicate directions in the field of the microscope, it being assumed that the observer always faces north.

MINERALS

AND

THE MICROSCOPI

BY

H. G. SMITH
A.R.C.S., B.Sc., F.G.S.

University Reader and Head of the Department of Geology
Queen Mary College

PREFACE TO THE FOURTH EDITION

KINDLY critics have made several suggestions for
the improvement of this book, and some of these
have been adopted in this new edition. The chief
alterations, however, have been made in the sec-
tions on Igneous Rocks and Metamorphic Rocks.
These have been re-written with the object of
making them more comprehensive in scope. It is
impossible to acknowledge all the sources from
which information has been derived, but particular
mention should be made of Dr. Harker's book on
Metamorphism and the Address by Professor
Read on Metamorphism and Igneous Action.
These publications represent very different points
of view, each in its own way is admirable, and
should be read by all serious students of
Petrology. References to these works will be
found in the list at the end of this book.

H. G. SMITH.

February, 1940.

PREFACE TO THE FIRST EDITION

THE object of this book is to help the beginner over his initial difficulties in the study of petrology. Teaching experience extending over some years has convinced me that the difficulties met by the student are far greater than is commonly supposed by those who have forgotten their own early trials, or whose mental equipment was such as to enable them to escape the pitfalls waiting for their less fortunate fellows.

Even a series of lectures by a teacher of undoubted qualifications is not sufficient; the subject matter is so new to most students that very few are able to absorb the facts as rapidly as they are placed before them. It is felt that a good course of lectures and practical work requires amplification by a book whose aim is to smooth over difficulties of this kind.

Amplification of such a course, then, is the chief aim of this work. It is hoped, also, that those who are not able to attend a course of lectures may profit by the instruction contained herein. A point of primary importance, however, is that this book is not intended to serve as a substitute for the examination of thin sections.

The list of minerals described is far from being complete, but some care has been expended in the selection and arrangement of those dealt with, and

it is hoped that when a student has worked through them, he will be competent to, and desirous of, examining the minerals less commonly met with in thin section.

The section on petrology is designed to bridge over the gap usually left by text books on the subject, and should be used in conjunction with such a book as Harker's Petrology for Students, or Hatch's Text-book of Petrology.

It has been found necessary to assume that students have a knowledge of elementary physics and of crystallography. The former may quite safely be assumed, but the latter assumption is probably more dangerous; a good and simple description of the subject, however, will be found in the latest edition of Rutley's Mineralogy, a book which will be found extremely useful in other respects.

My thanks are due to the Rector of the Imperial College and to Professor Watts for permission to use the apparatus of the college in the preparation of the photographs reproduced in this book, also to my colleague, Mr. H. H. Read, for reading through the proofs and for many helpful suggestions.

H. G. SMITH.

April, 1914.

PREFACE TO THE THIRD EDITION

THE continued popularity of this book is evidence that it has responded to a demand by students. It is felt, however, that in consequence of increasing knowledge and the development of new ideas regarding Petrology, the second part of the work has become out of date. The whole of that section has therefore been re-written.

Theories are erected on the foundation of observation and experiment, and the ideal book would commence with a detailed description of the rocks, and conclude with an exposition of prevalent theories. In this case, however, the attempt is made to give material which will supplement the knowledge gained during the study of actual specimens and thin sections. If the student has made, or is making, some efforts along these lines, something like the ideal sequence is followed; and the hope is expressed that the method of treatment will give some life even to the study of inanimate materials like rocks.

H. G. SMITH.

June, 1933.

CONTENTS

LIST OF PLATES

xi

DESCRIPTION OF
A PETROLOGICAL MICROSCOPE

THE foot forms a support for the whole instrument, the pillar being attached to it by means of a joint which allows movement on a horizontal axis. The pillar supports the tube at its upper end, and the stage, RS, at the lower end; the adjustments, A_1 and A_2, give rise to a movement of the tube with reference to the pillar so as to cause the objective, O, to approach or recede from the stage. O and O_1 are the two objectives; these have different magnifying powers, and either may readily be placed in line with the tube so as to come into use. The eyepiece, E, is a system of lenses fitting into the upper end of the tube; it brings the magnified image to a focus when the objective is properly adjusted.

RS, the rotating stage, supports the microscope slip, which is held in position by means of the two clips. The stage is graduated into degrees, and may be rotated through a known angle, the angle being read by means of a fixed point or a vernier attached to the pillar. The mirror, M, receives light from some source of illumination, and when placed at the proper angle, transmits the light along the axis of the instrument to the eye.

The polariser, P, is a Nicol's prism placed beneath the stage; it is capable of rotation on its own axis, and may be swung aside when not required. A, the analyser, is also a Nicol's prism which is capable of rotation; when required, it is swung into position above the eyepiece.

Additional fittings, the object of which is to produce interference figures, are B, the Bertrand lens, and C, the converging lens. The converging lens is placed between the polariser and the stage, the Bertrand lens in the tube above the objective. The latter consists of a converging lens of the required focal length; it may be mounted in a carrier, so as to enable it to slide in and out of the tube as required, or may be fitted in the lower end of a draw-tube. The illustration shows the tube cut away in order to indicate the position of this lens when in use.

S and S_1 are two slots, into which the wedge or mica plate may be inserted when determinations of " sign " are to be made.

The above illustration shows at a glance the essential features of a Petrological Microscope by means of the letters underlined and the detail work. It will be found that the parts A. B. S. and S1 are differently situated in the microscopes supplied by various manufacturers.
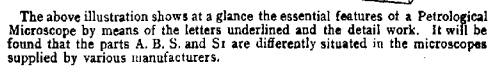
OPTICAL PROPERTIES OF MINERALS

CHARACTERS OF MINERALS IN ORDINARY TRANSMITTED LIGHT

THE first examination of the section should be made with the one inch objective; both polariser and analyser being swung out of the axis of the instrument.

As a rule, it will be seen that the thin section is made up of several minerals, some transparent, others opaque. For the present we shall confine our attention to the study of those minerals that transmit a certain amount of light; a method for the examination of opaque minerals will be described later.

Colour.—The light transmitted by the different minerals varies both in amount and kind; some minerals are almost opaque, others perfectly transparent. In some cases, the whole of the constituents of white light are allowed to pass through; these minerals are colourless. Other minerals, however, absorb some portion of the spectrum, with the result that the light reaching the eye has a certain colour—the colour complementary to that absorbed. This colour supplies us

with the first means of distinction between the rock-
forming minerals.

The section will probably contain several
examples of any particular mineral, and the student
will naturally expect that all these fragments will
exhibit the same colour, or will agree in being
colourless; but it must be realised that, while this
may be the case, it is not necessarily so.   Varia-
tion in the colour of the different individuals is
intimately related to the crystal symmetry. Should
the mineral in question crystallise in the cubic
system, all the fragments present in the section will
be either colourless or will transmit the same
colour; a good example is the mineral garnet, the
common varieties of which transmit a pink colour.
On the other hand, biotite, crystallising in the
monoclinic system, supplies us with an example of
a mineral which varies in colour according to its
orientation in the section. The different fragments
occupy all possible positions in the rock from which
the section is cut; consequently a section supplies
numerous cases.   Crystallographically, no two of
these are identical, and each case has its own
absorption.   The result is that the different frag-
ments of this mineral exhibit very different shades
of brown.   It will be seen that we must rely on
other characters to demonstrate that such fragments
are identical in composition.   There are many
cases, however, even in the same system, in which
all sections of a coloured mineral have much the
same shade; a good example is common augite.
Again, the mineral muscovite, also crystallising in
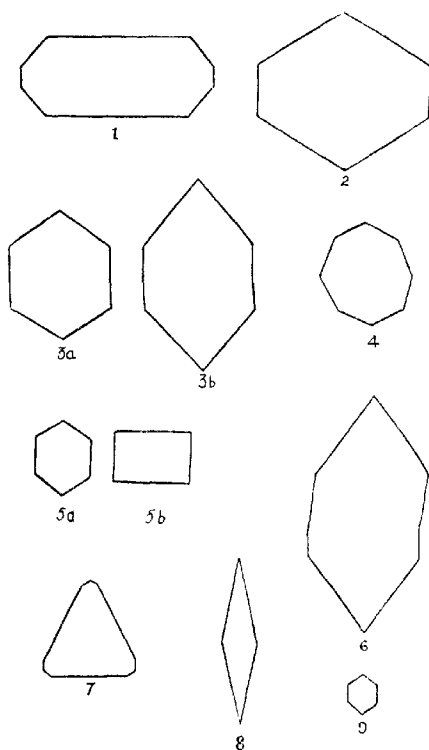
1. Augite.   2. Hornblende.   3*a*. Quartz—Basal section.
Transverse section.   Transverse section.   3*b*.   ,,   Vertical ,,

4. Leucite.   5*a*. Nepheline—Basal section.   6. Olivine.
                   5*b*.   ,,   Vertical ,,

7. Tourmaline—Basal section.   8. Sphene.   9. Apatite—Basal section.

the monoclinic system, is typically colourless in all its sections. The relationship of colour in thin section to crystal symmetry may be summarised as follows :—

Cubic system :—All sections of one mineral are colourless or exhibit the same colour.

Other systems :—The different sections are usually different in colour; but all may be colourless, or all may be similarly coloured.

Form.—The most useful rocks for microscopic investigation are those igneous rocks known as plutonic. These may be looked upon as aggregations of minerals which have crystallised from the fused state; and as the individual minerals have not all formed simultaneously, it will readily be understood that the first-formed minerals have had the best chance of developing that shape to which their own constitution would lead. The growth of the later-formed minerals has naturally been impeded by the first comers, and the one crystallising last of all has been compelled to fit itself into the space left by the earlier-formed crystals. It will be seen, then, that such rocks will show (1) minerals having their own form (idiomorphic); (2) minerals with their own form imperfectly developed; and (3) minerals whose form has no connection with their own constitution (allotriomorphic).

Further, even those minerals which are idiomorphic will show different outlines according to their position in the rock. The student will be able to form some idea as to the possibilities of variation in form by studying the case of a hexagonal prism

like a six-sided lead pencil. A longitudinal section would show a rectangle; a transverse section, a regular hexagon; an oblique section, as a rule, an irregular hexagon; the shape varying with the degree of obliquity. Other possibilities will occur to the intelligent student.

Having indicated the number of possible cases, we must warn the student that he will not often find perfectly idiomorphic constituents. When they do occur, however, they are extremely useful as a means of identification. Much more frequently he will find minerals giving merely indications of their form. The variations in form are so numerous that it is almost impossible to give summaries in terms of crystallography; it may, however, be stated that sections of cubic crystals are rarely elongated, while many sections of crystals with lower symmetry exhibit this character.

Cleavage.—Even a slight acquaintance with minerals as seen in hand specimen will be sufficient to enable the student to recall examples of minerals showing this tendency to break in definite planes. Calcite splits in three directions; in fact, it is almost impossible to break the mineral in any other direction. The common micas, muscovite and biotite, cleave in one direction with extreme facility; and gypsum also has one perfect cleavage. In thin section, these cleavages are seen as parallel straight lines. Minerals having more than one cleavage usually show more than one set of parallel cracks, those of the one set intersecting the others. The student must realise that these cleavages have a

definite crystallographic orientation; in the case of
the micas, the one perfect cleavage is parallel to the
basal pinacoid; the three cleavage directions of
calcite are parallel to the faces of a rhombohedron.
It must be understood also, that they are not neces-
sarily parallel to faces actually present in the
crystal; calcite, for example, rarely crystallises with
the form of the rhombohedron to the faces of which
its cleavages are parallel. The forms presented by
calcite crystals are numerous and bewildering to
the young student, but any one of these crystals
may be cleaved in the three directions which are
those of the faces of what is known as the funda-
mental rhombohedron. This constancy of cleav-
age direction for any mineral which shows cleavage
at all, supplies another useful means of identifica-
tion.

We find, however, a certain amount of variation
in the different sections of any mineral. Micas, for
instance, have one perfect cleavage; but in thin sec-
tion we see many examples in which no cleavage is
visible. The explanation is perfectly simple.
Consider the analogous case of a book; the cleavage
flakes of the mica correspond to the leaves of the
book. Let the book rest flat on the table, and
imagine it cut in vertical section; the cut surface
would show a series of parallel lines produced by
the intersection of the plane of section with the
leaves. A horizontal section would not, however,
show any cleavage, because it never cuts across a
leaf. It is necessary to point out, however, that
oblique sections do not always show cleavage. One

might expect that, as the horizontal section already
considered is the only one not cutting across the
cleavages, it would be the only one not showing the
cracks in section. This is not the case. If we con-
sider a series of sections varying from the perpen-
dicular to the parallel, we find the cracks becoming
less and less conspicuous, until, before the parallel
condition is reached, the cleavages become
invisible.

We have considered the case of micas in some
detail as they supply a very simple case, which
serves as a peg on which to hang an important
principle.
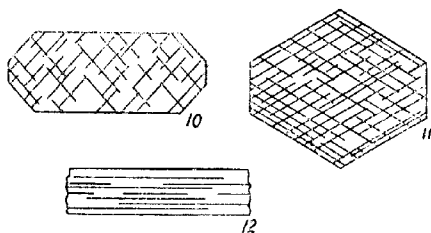
10. Augite.   11. Hornblende.   12. Biotite.

If we now pass on to the case of a mineral show-
ing two cleavages, we have to consider, in addition
to the presence of cleavage, the angle of inclination
between the cleavages. Hornblende (monoclinic)
is a common rock-forming mineral with two cleav-
age directions which are parallel to the prism faces.

A transverse section of four such faces would give a rhomb with angles of 125° and 55°; and these, therefore, are the cleavage-angles typically exhibited by this mineral in thin section. A vertical section, however, shows one cleavage-direction only; the reason should be quite clear after a little consideration.   Some difficulty is encountered by many students who fail to understand the value usually attached to a cleavage angle; it is quite true that the angles formed by the intersection of the cleavages, as seen in oblique sections, would vary with the degree of obliquity if they were visible. It should be remembered, however, that if section and cleavage are not inclined at or near a right angle, the cleavage cracks will not be visible; consequently, when the two cleavages of hornblende are seen in section, that section is approximately transverse, and the characteristic angles are exhibited. Augite is another monoclinic mineral with prismatic cleavages, but here they are almost at right angles; this difference in the cleavage angles is extremely important as a means of distinction between the two minerals.

Refractive Index.—For a full account of this property of solids and liquids, the student is referred to text books on Light; we shall here consider only those aspects which directly concern us.

A rock section is an extremely thin slab of rock which is sandwiched in between layers of a substance known as Canada balsam; this sandwich rests on a glass slip and is covered by another and much thinner slip of glass, but these may be

ignored. We are concerned here only with the substance in contact with the minerals making up the rock.

It is well known that colourless transparent substances are visible only when they differ in optical density (refractive index) from the fluid in which they are immersed; and the greater the difference between the two substances, the more conspicuous will be their limiting surfaces. An instructive experiment is to powder common glass and drop it in water. Better still, powder a fragment of the mineral cryolite and drop the powder in water; it is with the greatest difficulty that the mineral can be seen when immersed in the liquid, and one is inclined to believe that it has passed into solution. It is invisible, however, merely because the two substances, cryolite and water, have almost exactly the same refractive index.

We are now in a position to make a general statement. The visibility of a transparent solid depends on the difference in refractive index between it and the fluid in which it is immersed. Minerals in thin section may be considered to be embedded in a liquid—the Canada balsam. On examining the margins of the transparent minerals in section, we find, by working round the edges of the section where the minerals are in contact with Canada balsam, that some of the edges stand out conspicuously, while where other minerals come in contact with Canada balsam, the junction is comparatively inconspicuous. The minerals are in contact with the mounting medium

also on their upper and lower surfaces, and these supply us with additional information. In consequence of the method of preparation of thin sections, these surfaces are rough; they are grooved and·pitted by the powders employed in the grinding. Those minerals differing in refractive index from that of the mounting medium show these rough surfaces when carefully focussed; on the other hand, those constituents approximating in refractive index to the Canada balsam always appear to be smooth in consequence of this approximation. Clearly, then, we have here a means of determining by mere inspection whether or not a particular mineral has a refractive index which is near to or distant from that of Canada balsam, 1·54.

But it is necessary to determine whether the refractive index of the mineral in question is higher or lower than that of Canada balsam; and a means of making this determination is supplied by BECKE'S TEST. Using the high power objective, focus carefully an edge of the mineral where it is in contact with the mounting medium, choosing an edge which is as clean as possible; if a small fragment of the mineral has become detached from the rest of the rock and thus lies surrounded by Canada balsam, it will supply the ideal conditions. Rack the tube up and down a little on each side of the position of focus, being careful not to push the objective through the slide, an accident which occasionally happens to the beginner. It will be seen that, when the fragment is slightly out of focus, it is surrounded by, or encloses, a ring of light, which

expands or contracts as the tube is alternately raised and lowered.

There are two cases. The refractive index of the mineral is (1) higher, and (2) lower, than that of Canada balsam, 1·54. It is convenient to consider only what happens when the objective is being raised. In the first case, when the mineral is denser than the mounting medium, the ring of light will contract; it will pass from the Canada balsam to the mineral. When the mineral is the less dense substance, the light passes from the mineral to the balsam.

In both cases, as the objective is raised, the light passes from the substance with the lower, to that with the higher refractive index. It is thus possible, by this test, to eliminate all those minerals which differ from the one under consideration in being higher or lower than Canada balsam in refractive index; and the method of elimination will sometimes be found extremely useful in making identifications. A concave mirror should always be used in making this test, and a diaphragm will be found useful in difficult cases. The existence of this more intense illumination depends on the property of total internal reflection, as the light impinges on a surface limiting a dense substance. In some cases it is possible by this method to compare the refractive indices of two minerals in contact, but the contact is not always sufficiently good to give results.

As examples of case 1, topaz, apatite, or olivine gives good results. Fluor, nosean, and leucite supply good examples of case 2.

When reference is made to " the refractive index " of a doubly refracting mineral, it must be understood that the mean refractive index is referred to, also, that that value has been obtained when using sodium light.

Alteration.—Orthoclase felspar supplies us with a good example of a mineral which is liable to decomposition on exposure to atmospheric conditions. If the rock from which the section has been cut is " fresh," this mineral is quite colourless and transparent; but when decomposed it has lost its transparency, and has become a mere aggregate of countless greyish semi-opaque particles of the hydrated mineral, kaolin. Some fragments are in an intermediate condition—altered merely in parts; the student should examine slides containing the mineral showing different degrees of alteration. The case of orthoclase is specially important because the tendency to decomposition is often useful in distinguishing this mineral from quartz, which it may strongly resemble.

Olivine, also, is unstable under atmospheric conditions, and is frequently seen more or less altered to the green mineral serpentine. The mode of alteration is very characteristic. Olivine, when fresh, is a colourless mineral, usually traversed by irregular cracks, and it is along these that the alteration product first developes. Later stages show that these " channels " of serpentine have become wider, the " islands " of fresh olivine have become smaller, and the last stage shows the mass of serpentine having the form of the olivine from

which it was derived. The serpentine is commonly associated with granules of black iron oxide, another product of the decomposition of the original olivine.

Biotite is another unstable mineral, the product in this case being the green mineral chlorite. Excellent examples showing different stages of alteration are obtainable in different sections, ranging from the fresh brown biotite to the pseudomorph in chlorite.

Inclusions.—In some few cases, minerals may be seen to contain inclusions of other substances which are useful in making identification. The best examples are seen in some specimens of leucite, which may show small fragments of other minerals (notably green augite) arranged in a ring. The student, however, must not expect all specimens of leucite to exhibit this character.

Other minerals contain inclusions, but the character is not often of service in distinguishing the mineral. Quartz may show liquid and gas inclusions, and orthoclase sometimes contains glass.

Zoning.—It is often found that a crystal is not uniformly coloured, but exhibits an arrangement of colour bands which are concentric with the exterior. Nosean, for example, is commonly distinguished by a well-marked brown periphery, although the centre is colourless. Tourmaline, brown garnets, and pyroxenes frequently show a succession of concentric rings of colour; this variety of zoning is known as colour-zoning. A similar structure,

already mentioned under the heading of inclusions, is exhibited by some minerals in consequence of their manner of arranging inclusions. Leucite is the most striking example; but a less conspicuous zoning by inclusions is sometimes seen in felspars and pyroxenes.

Zoning is most commonly exhibited by the minerals which are grouped together as isomorphous, and no better example can be found than the Albite-Anorthite series of plagioclase felspars. It is often found that the crystal is not homogeneous, but is built up of successive shells, each of which has a composition which is different from that of its neighbours; the crystal has commenced its growth as one member of the series, but has received additions of ever-varying composition. In consequence of this structure, the mineral being liable to decomposition and the several shells being unstable in different degrees, the weathering action has picked out the less stable layers and has emphasised the zonal nature. When the kaolinised layers have received a stain of iron oxide, as sometimes happens, the zoning becomes still more striking. But even when the felspar is quite fresh, the zones are sometimes visible in consequence of the difference in refractive index between them. The colour-zoning of tourmaline, pyroxenes and garnets, is also to be attributed to an isomorphous relationship; it happens to be the case that the different members of the particular series are differently coloured.

CHARACTERS OF MINERALS IN
REFLECTED LIGHT

HITHERTO we have considered only the case of minerals which, in section, transmit a certain amount of light; but some minerals, even in thin section, are quite opaque, and a special method of investigation is employed for their identification. The mirror must be tilted so that no light comes from below, the tube placed vertically, and the examination should be conducted near a window or other source of light, so as to allow of reflection from the upper surface of the slide. In these circumstances, magnetite shows a black metallic surface if fresh; it is associated with a red alteration product (hæmatite) if decomposed. Ilmenite (titanoferrite) if fresh, has also a black metallic appearance, but decomposition results in the formation of a whitish substance (leucoxene) which may be arranged in triangular areas; but this geometrical arrangement is not always seen. Iron pyrites shows a brass-yellow colour and metallic lustre.

This test may also be employed with advantage in the examination of some minerals which are not opaque; the distinction between quartz and felspar may sometimes be made advantageously by observing the mineral in question in reflected light. Any alteration of the felspar is easily seen by this method.

It should be remembered that in all the methods of examination to be described later, transmitted light is to be used.

15

CHARACTERS OF MINERALS WITH THE
LOWER NICOL INSERTED

HAVING completed a survey of the characters employed in mineral identification when the microscope is used without either nicol, the attention of the student may be directed to the characters to be observed when the lower nicol (the polariser) is in position in the axis of the instrument, the upper nicol (the analyser) still being pushed aside, as in the preceding section.

The Nature of Light.—In order to understand the phenomena, it is necessary first to realise some elementary facts as to the nature of light and the construction of the Nicol's prism.

As light may be transmitted through what is known as a vacuum, it is necessary to assume the existence of a substance pervading all space, by means of which the transmission is effected. This substance is known as the ether. It is quite certain that light is transmitted as a consequence of a series of vibrations which take place at right angles to the direction in which light is travelling, and the theory formerly accepted was that the ether particles themselves performed these vibrations to and fro without undergoing any movement along the line of propagation of the ray. The theory has now been considerably modified, and a theory of oscillation,

not of the particles themselves, but of their electrical condition, is now held to account for the facts more satisfactorily. But these oscillations or vibrations certainly do take place, and they take place at right angles to the direction of propagation of the light. A ray of ordinary light performs its vibrations in all directions possible subject to this limitation, that is, in all the directions perpendicular to the direction of transmission; but light which has passed through a nicol performs all its vibrations, not merely perpendicular to this direction, but parallel to a definite line which fulfils this condition. Such light, performing its vibrations in one plane only, is said to be polarised, and we have now to learn something about the construction of a "nicol" in order that we may realise the conditions of investigation.

The Double Refraction of Calcite.—The nicol is made of a clear variety of calcite known as Iceland Spar, a substance possessing to a remarkable degree the power of splitting a ray of entering light into two—the property we know as double refraction. The mineral has an extremely good cleavage in three directions, and, split along these cleavages, it yields a fragment of the form known as the rhombohedron. Light entering such a fragment perpendicularly to one of the cleavage planes is split into two rays, and, in consequence, any object viewed along such a perpendicular is doubled; two images reach the eye. The most satisfactory demonstration of this fact is obtained by resting the fragment on a sheet of white paper on which a small

blot of black ink has been made. Seen from above, such a spot is doubled. Now rotate the fragment. It is seen that one of the images remains stationary, while the path of the other is the circumference of a circle with the stationary image as centre. The stationary image behaves just as if the crystal were a slab of glass; it is therefore said to be produced by the ordinary ray. The ray producing the movable image, on the other hand, does not obey the ordinary laws of refraction. To anyone who has studied only singly refracting substances, its behaviour appears to be quite extraordinary, and it is therefore known as the extraordinary ray.

By looking at the surface obliquely, we can see that the ordinary image appears to occupy a higher position inside the fragment than does the extraordinary image. In other words, the density of the crystal for the ordinary ray is greater than for the extraordinary ray, or, the velocity of the extraordinary ray is greater than that of the ordinary ray. The fact that two such rays travelling in a doubly refracting crystal have different velocities, is extremely important to the student who wishes to understand what follows, and this experimental demonstration of the fact should help materially to fix the ideas.

We have seen, then, that a ray of light incident normally on a face of such a rhombohedron is split into two, each ray having its own path and a velocity which depends on the nature of the crystal. Still further information may be obtained if the two spots are examined through a nicol. The nicol

may, for the present, be considered as an instrument capable of transmitting only that light which vibrates in a direction known as the principal section—the line A.B. (Fig. 13). When the nicol is
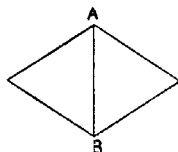

13. The nicol seen from above.

rotated on a vertical axis, it is seen that the two spots appear and disappear alternately, and that a rotation of 90° is necessary to produce this alternation. Granting our assumption as to the direction of the vibrations transmitted by the nicol, it is easily demonstrated that each ray emerging from the cleavage fragment is polarised (performs its vibrations parallel to one line only), and that the two vibration directions, that of the ordinary ray and that of the extraordinary ray, are at right angles. Clearly, then, if it is possible to prevent the emergence of one of these rays from the Iceland spar, an efficient instrument for the production of polarised light may be obtained. Such an elimination is effected by the nicol. Before its operation can be understood, however, the student must realise what is meant by total internal reflection.

The Nicol.—A ray of light passing obliquely from one transparent substance to another, is refracted at the surface, the amount of refraction being proportional to the difference in optical density between the two substances. A ray passing from the less dense to the more dense substance is refracted towards the normal. Now, consider

what happens when a ray meets the surface from
the more dense side, taking the case of glass and
air. A ray such as B. C. D. (Fig. 14) passes from
one substance to the other, but is refracted away
from the normal—the angle of incidence is less than
the angle of refraction. The angle of incidence for
which the angle of refraction is 90° is of particular
importance, and is known as the critical angle;
when the angle of incidence is smaller, light passes
to the rarer medium; when the angle of incidence is
greater, no light emerges; it is reflected from the
surface back into the denser medium. If then, two
rays impinge on such a surface, with angles of in-
cidence less and greater than the critical angle, one
will pass to the rarer medium, the other will be
totally reflected at the surface. The one succeeds
in passing the surface, the other fails.
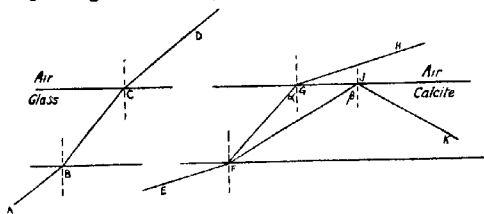

14. Refraction.   15. Refraction and total reflection.

Figure 15 represents the case of a doubly refract-
ing substance where the entering ray, E. F.,
divides; one ray, E. F. G. H., emerges, because *a*
is less than the critical angle; another ray,
E. F. J. K., is totally reflected at J., because β is
greater than the critical angle.

The student is now in a position to understand
the principles on which a nicol is constructed.
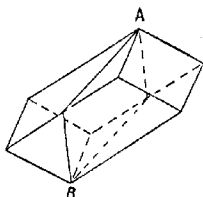
16. The film of Canada balsam
within the nicol.
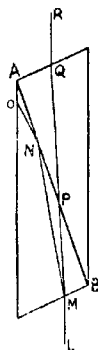
17. Separation of the two
rays by the nicol.

An elongated cleavage rhombohedron of Iceland
spar is cut into halves, as shown in Figure 16, and
the two cut surfaces cemented together with Canada
balsam ; the two end faces are ground down so as to
convert an angle of 71° to one of 68°. Figure 17
shows a section of the nicol where the plane of the
paper is perpendicular to the film of Canada balsam
A. B. with the vertical edges parallel to the axis of
rotation when in position in the microscope. A ray
of light entering at the lower surface is split into
two. The ordinary ray is the more refracted, meets
the film of balsam at N. with an angle of incidence
greater than the critical angle, and is consequently

totally reflected to O, as the refractive index of the
calcite for the ordinary ray is greater than that of
the balsam (1 ·54). None of its light emerges at the
upper surface of the nicol.

The extraordinary ray is less refracted, and takes
the path M.P.Q.R., penetrating the film of balsam
at P., because the angle of incidence is less than
the critical angle.

The vibrations of the extraordinary ray are exe-
cuted in the plane of the paper; the emerging light
is made up entirely of extraordinary rays; and,
consequently, the desired end is achieved by this
construction.   Only plane polarised light is trans-
mitted by the nicol.   The vibration direction of
this emerging light is the direction of the shorter
diagonal of the end face as seen from above.

Pleochroism.—We are now in a position to con-
sider the microscopic examination of thin sections
when the lower nicol, the polariser,
is in position in the axis of the instru-
ment underneath the stage.

The light reaching the section has
previously passed through the polar-
iser, and is consequently performing
its vibrations parallel to the principal
section of that nicol, which, although
the nicol is capable of rotation, we
shall, for purposes of description, consider to be
fixed in an E.W. direction. If now a section con-
taining the mineral biotite is placed on the stage,
and the stage rotated, it will be seen that the mineral
changes colour from a pale brown to a dark brown,
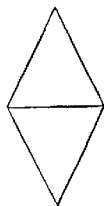
18. Plan of the
polariser in posi-
tion

and that a rotation of 90° is necessary in order to produce the maximum change.
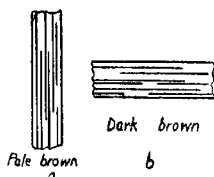
19. The pleochroism of biotite.

This property of certain minerals, exhibited very strikingly by biotite, of changing colour when thus examined, is known as pleochroism. It supplies us with an extremely valuable means of distinguishing many minerals with the polarising microscope.

The case of biotite will be easily understood if it is remembered that such a section is capable of transmitting light vibrations in two directions only. These two directions are at right angles, parallel and perpendicular to the cleavage direction. In position (a) Fig. 19, the whole of the light transmitted vibrates in one of these directions, and the mineral absorbs its minimum amount of light. In position (b), the whole of the light transmitted vibrates in the other of these directions, and the mineral absorbs its maximum amount of light. In an intermediate position, some light is transmitted vibrating in each of the two vibration directions, each direction absorbs its own amount of light, and consequently the transmitted light is intermediate in shade between the two pleochroism extremes.

Other common minerals affording good examples

of pleochroism are, hornblende (pale green to dark green or pale brown to dark brown); tourmaline (usually pale brown to dark brown); andalusite (colourless to pink); ægirine (usually a rich yellow to blue green). In all these cases the minerals are doubly refracting, and, as a rule, their sections have two rectangular vibration directions with different powers of absorption. It must be understood, however, that the strength of the pleochroism depends on the direction in which the section is cut; for instance, basal sections of biotite exhibit very feeble pleochroism, while basal sections of tourmaline are absolutely non-pleochroic. This crystallographic variation emphasizes the necessity for examining as many fragments of the mineral as are available in the slide before an identification is made.

Pleochroic Haloes.—Certain minerals, otherwise colourless in thin section, show curious circular brown areas, each of which contains at its centre an included fragment of some other mineral. These brown patches change colour when the section is rotated above the polariser; they are, in fact, pleochroic areas in an otherwise colourless section. It is quite certain that the including mineral has acquired this property in consequence of the presence of this minute inclusion. Several theories have been put forward to account for these pleochroic haloes, but it has now been satisfactorily proved that the development of colour around the inclusion is the result of the fact that such an inclusion is radio-active, and that its ejected

particles have produced an ionisation effect on the mineral in contact. Minerals showing these haloes are muscovite, cordierite, tourmaline, and biotite. The last two minerals are not colourless, even in thin section, but in their case the colour has been rendered more intense around the inclusion.

Twinkling.—A change which cannot be called pleochroism takes place when sections of the mineral calcite are rotated over the polariser. Calcite is doubly refracting, and consequently, most of its sections possess the two rectangular vibration directions for transmitted light. When the rotation takes place, the mineral shows, at one time, rough surface, well defined borders, and conspicuous cleavages; at another time, smooth surface, faintly defined borders, and inconspicuous cleavages. The change is from a mineral with a high refractive index to one with a low refractive index, and these extremes of relief are exhibited when the two vibration directions of the calcite in section come to be parallel in turn with the vibration direction of the light emerging from the polariser. This means that each of the two vibration directions has its own refractive index. A rapid rotation of the stage (or of the polariser beneath it) produces a rapid change of relief which cannot be better described than by the name of twinkling. This is quite different from pleochroism, which is essentially a change of colour, whereas the calcite remains quite colourless. Other minerals with a high double refraction show the same effect, not-

ably the other rhombohedral carbonates, but few
other minerals show a conspicuous change of relief,
though theoretically, all doubly refracting sections
ought to show some such change. Only in a few
cases, however, such as the one cited, is the change
sufficiently great to be worthy of consideration in
practice.

Crystallographic Summary.—It is a matter of
some difficulty to tabulate the pleochroic properties
of minerals crystallographically in such a way as to
be of assistance to the student, but it may be stated
quite definitely that the following sections are non-
pleochroic:—

All colourless sections.

All sections of cubic minerals.

Basal sections of dimetric minerals.

Other sections may show pleochroism.   Some
show a striking change of colour, others merely a
slight change; in still others the absorptive powers
of the mineral for the two vibration directions are
so nearly equal that even the most imaginative
observer fails to notice any change of shade or
colour.

CHARACTERS OF MINERALS BETWEEN CROSSED NICOLS

WHEN minerals are to be examined between crossed nicols, both analyser and polariser must be placed in the axis of the microscope, and, moreover, the two nicols must be rotated to such positions that, with an empty stage, no light reaches the eye. In order to simplify this adjustment each nicol may be provided with a catch which indicates the correct position. It must be borne in mind by the beginner that if the two nicols are used, they *must* be in the crossed position, and neither may be rotated; rotation of the stage, however, is not only permissible, but essential. We have already seen that the light transmitted by the polariser vibrates only parallel to an E.W. line—the principal section. The analyser is similar to the polariser in all respects except that of position; its principal section is in a N.S. direction. The result of this "crossing" of the two nicols is that the emerging extraordinary ray of the polariser becomes the ordinary ray of the analyser, and is totally reflected from the film of balsam. With an empty stage, the polarised light from the lower nicol is allowed a free passage to the upper nicol, and, consequently, the whole of the light transmitted by the lower is stopped by the upper; the field is quite dark.

27

A plate of glass, or any other singly refracting substance placed upon the stage does not produce any alteration of this condition, the reason being that it has no power to change the vibration direction of the entering light. Canada balsam is another singly refracting substance, hence, we are quite certain that if any alteration is produced in the dark field when a microscope slide is placed on the stage, such alteration is due entirely to the minerals in the slide.

Isotropism and Anisotropism.—Some mineral sections have no power to produce any illumination; they are singly refracting and consequently are quite dark between crossed nicols. They remain in that condition during a complete rotation of the stage, and are said to be ISOTROPIC. All sections of minerals crystallising in the cubic system, and basal sections of minerals crystallising in either of the dimetric systems, are isotropic. All other sections are ANISOTROPIC, that is, they are alternately dark and illuminated when the stage is rotated.

Extinction.—It is found that anisotropic sections, for most positions of the stage, transmit light of a certain colour, but that, from time to time during rotation they become dark—they are said to extinguish; and if the angle of rotation is taken, it will be found that extinction takes place at intervals of 90° exactly. For instance, most sections of the mineral apatite (crystallising in the hexagonal system), which are elongated, colourless, have a high refractive index, and a basal cleavage,

when rotated between crossed nicols, show a colour which is grey; this is extinguished when the edges are N.S. or E.W. Another good example is supplied by the mineral muscovite. This usually shows no definite outline, but seen in ordinary light it is colourless, and shows a well-defined cleavage. The colour between crossed nicols is bright pink or green, but this colour is extinguished when the cleavage is N.S. or E.W. Both these cases show straight extinction, that is, extinction takes place when some definite direction, edge or cleavage, is placed N.S. or E.W.

Other minerals, however, although they extinguish at intervals of 90°, do not extinguish in these positions, but at some other position during rotation. Most sections of the mineral augite, for instance (pale brown, high refractive index, and showing one or two good cleavages) extinguish when the edges of the fragment are not parallel to either of the rectangular cross-wires in the eye-piece of the microscope—placed N.S. and E.W. Such sections show oblique extinction, and it is sometimes useful to know the position at which extinction does take place. This angle of extinction is measured either from the N.S. or the E.W. cross-wire. In order to determine its value, the stage is first rotated until the mineral fragment is extinguished, when the angular position of the stage is read; the stage is then rotated until the crystal edge is parallel to one of the cross-wires, when the stage reading is again taken; the difference between the two readings gives the angle of extinction. It will

be seen, however, that this is only one of two
possible values; the other value would have been
obtained if rotation had brought the edge parallel
to the other cross-wire. These two values are, of
course, complementary, and it is usual to take the
smaller value as the angle of extinction.

Polarisation Colours.—We may now proceed to
consider the reasons why a section in one position
gives a polarisation colour, and in another becomes
extinguished. It has already been seen (i) that if
light leaves the section vibrating as it entered (as it
left the polariser) it must suffer elimination in the
analyser; (2) that a doubly refracting section has
two rectangular vibration directions which are the
only possible directions of vibration in the section;
(3) that extinction takes place at intervals of 90°.

If we suppose that the mineral section is in such a
position on the stage that its two vibration direc-
tions coincide with the cross-wires, N.S. and
E.W., the light emerging from the polariser will
travel through the section vibrating exclusively
along the E.W. vibration direction in the section,
and will emerge from it still vibrating E.W., that
is, in such a way as to be totally reflected by the
analyser. A similar result must be obtained if the
section is turned through 90°, for then the other
vibration direction has come to lie E.W., and again
total reflection is effected by the analyser. Such
positions of the section, then, must secure
extinction.

The reason for the production of polarisation
colour when the vibration directions are not parallel

to the cross-wires, is not quite so simple; but it is
not very difficult to obtain some idea as to the
causes. It must be realised that the two vibration
directions in the section are the only two possible
for light penetrating the mineral, and also that
while each vibration direction secures retardation
of the light, the light which has vibrated in one of
these directions has suffered a retardation which is
not equal to that suffered by the other. Suppose
that these directions make angles of 45° with the
cross-wires. The light emerging from the
polariser is vibrating E.W. On entering the sec-
tion it divides; some vibrates N.E : S.W., the re-
mainder N.W : S.E. The two rays travel up to the
analyser, and although there must be some resolu-
tion of the two into N.S. and E.W. vibrations, the
remainder reaches the analyser vibrating in other
directions. The essential point is that this light
has traversed the section vibrating in different
directions, and consequently there is a relative re-
tardation. On entering the analyser, the vibration
directions are reduced to two only : E.W. and N.S.
The E.W. vibrations are totally reflected from the
film of balsam, and it only remains to consider
the N.S. vibrations. Some portion of the light has
traversed the section vibrating N.E. : S.W., the
remainder has traversed the section vibrating
N.W : S.E. That is, there are two rays vibrating
in the same plane with a difference of phase, and
this difference is comparable with the wave lengths
of light. Clearly then, the conditions are such as
to produce interference, for it is evident that for at

least one of the constituents of white light, the half wave length must divide into the relative retardation so as to give some odd whole number. Disregarding other kinds of interference, this particular kind must result in the elimination of the colour in question ; the complementary colour (the polarisation colour) penetrates the analyser, and reaches the eye. The student will see that the polarisation colour depends entirely on the amount of the relative retardation effected between the two rays traversing the mineral section ; this is quite unlike the case of pleochroism, which depends on the difference between the absorptive powers of the two vibration directions.

In considering the difference between the two retardations, it is necessary to take into account : —

    I. Thickness of section.

    II. Crystallographic orientation of section.

    III. Nature of mineral.

I. That the polarisation colour is dependent on *the thickness of section in the* case of anisotropic minerals, is beautifully demonstrated when a *wedge-shaped fragment is placed between crossed nicols. Crystalline gypsum* is a suitable material* for experiment. This mineral, which possesses a perfect clinopinacoidal cleavage, should be cleaved into a flake about one-sixteenth of an inch in thickness, and from this a small rectangle measuring about 1in. × ½in. should be cut with a knife, care being taken that the edges of the rectangle are parallel to the two vibration directions. This can be

* Quartz is equally useful.

done by drawing an E.W. or N.S. line on the flake
when it is in extinction between crossed nicols.
The rectangle should be cemented with Canada
balsam near the end of a glass slip, half an inch in
width, and carefully ground down so as to make
one end as thin as possible, while retaining the full
thickness at the other. When such a wedge is
mounted and placed between crossed nicols in a
N.E : S.W. or a N.W : S.E. position, it is seen to
exhibit the succession of gorgeous colour-bands
known as Newton's Scale. Every student should
take an early opportunity of examining this scale,*
as no amount of description will serve to give an
adequate idea as to the nature of the colours. It
will be necessary to refer repeatedly to this scale,
but for the present we may look upon it simply as a
complete proof that the particular polarisation
colour produced depends on the thickness of the
doubly refracting mineral through which the light
has passed, the greater thickness effecting a greater
relative retardation.

II. That equal thicknesses of the same doubly
refracting mineral produce different polarisation
colours when the sections have different crystallo-
graphic orientations, may be easily proved with
almost any such mineral. Quartz supplies a very
suitable case. If three sections are cut, say, parallel
to the basal pinacoid, the rhombohedron, and the
prism, ground down to the ordinary thickness, and
mounted, they will show quite different colours
between crossed nicols; the basal section is

See frontispiece.

isotropic, the other two are anisotropic; the rhombohedral section polarising in grey, and the prismatic section in yellow. Barytes is another common mineral giving good results; the macropinacoidal section polarises in yellow, and the brachypinacoidal section in bright pink or green.

III. That the polarisation colour depends on the nature of the mineral may be demonstrated by mounting prismatic sections of quartz and calcite side by side. The quartz polarises in yellow, and the calcite in pale grey.

Birefringence.—All these polarisation colours in the case of anisotropic sections are due to the amount of relative retardation effected in the section —the difference between the velocities of the two rays travelling in the section, or, expressed differently, the difference between the two refractive indices, the retardation increasing, of course, with increase of thickness. Taking quartz as an example, we have seen that differently oriented sections produce different polarisation colours; if these colours are compared with those of Newton's scale, it will be seen that all three colours are found near the thin end of the wedge—low down in the scale; the yellow is the highest of the three, and this colour must be produced by that section of the mineral for which the difference of refractive indices is greatest. No other section of quartz will show polarisation colours higher in the scale than the yellow produced by the prismatic section; that is, such a section contains the two vibration

directions having the maximum velocity difference
for the mineral. This difference is best expressed
numerically as a difference between the two
refractive indices.

It may be demonstrated experimentally that
when the light vibrates parallel to the *c* crystallo-
graphic axis of quartz, the refractive index is
1.553, and that when the vibrations take place at
right angles to this direction, the refractive index
is 1.544. The difference, .009, is clearly a measure
of the strength of the double refraction for this
particular mineral, and this value is the birefring-
ence.

Every doubly refracting mineral agrees with
quartz in this respect, that it has one particular
section containing the two vibration directions
giving the maximum and minimum velocities for
the mineral. Light vibrating in these directions
has the maximum difference of refractive index for
the mineral; the difference is the birefringence of
that mineral, and, stated numerically, gives us
some idea as to what polarisation colours the
section of ordinary thickness is capable of produc-
ing.

Newton's Scale.—As it is often convenient to
refer to these colours in terms of Newton's scale,
it is necessary to examine this more closely.
Examining these colours, beginning at the thin end
of the wedge, we see that the first few colours are,
dark grey, light grey, white, yellow, and red; these
constitute what is known as the first order. The
succeeding colours include at intervals, bands of

red or pink, the pink becoming paler and paler
until it is indistinguishable from pale grey or
white.   These repeated bands supply a useful
means of splitting up the scale into orders, each
band terminating an order.   It is difficult to state
how many orders are exhibited by such a wedge,
as, to some eyes, a colour high up in the scale may
appear to be pink or green, while to others it is
simply a white or grey.   However, seven of these
orders are distinctly visible; higher colours may
be referred to as whites of a high order.   No two
orders exhibit quite the same colours, but only
practice will enable the student to state definitely
on examining mineral fragments between crossed
nicols, to what order exactly the colour belongs.
The first order colours are fairly characteristic;
those of the second and third orders are the
brightest in the scale; those of the higher orders
become more and more pale.   It is well for the
student to realise that it is not advisable to use the
words high and bright as synonyms; the higher
colours in the scale are not bright.

An anisotropic section, colourless in ordinary
light, shows when between crossed nicols a colour
which is due entirely to interference; but the case
of an anisotropic mineral section which absorbs
some constituent of white light is not quite so
simple.   Muscovite,   which   is   colourless   in
ordinary light, polarises in bright pinks and
greens; biotite, with approximately the same bire-
fringence, usually shows only a greyish brown.
The reason for this is, of course, that biotite shows

interference colour and absorption colour simultaneously. Tourmaline and brown hornblende supply other examples of this masking of the polarisation colour; while brown sphene, whose polarisation colour is a high order grey, shows between crossed nicols a colour not noticeably different from the absorption colour. One can only say of such a section of sphene, that it is anisotropic.

A few minerals, placed between crossed nicols, show what are known as ultra-polarisation colours. These colours are not to be found in Newton's scale, and are shown only by a few minerals, all with a very low birefringence. Chlorite, a monoclinic micaceous mineral, and zoisite, an orthorhombic mineral allied to epidote, occasionally show these ultra-blues or ultra-browns. The most satisfactory explanation of these polarisation colours is that the section is isotropic for some colours and anisotropic for others.

Twinning.—The observant student has already noticed that while some mineral sections polarise and extinguish as a whole, differences of colour being easily explainable as the result of variations in thickness, some particular mineral fragment is divided into two areas, the dividing line being straight, and usually sharply defined. Of these two areas, one is in a position of extinction when the other is illuminated, and vice versa. Moreover, the polarisation colours of the two areas are unlike. Orthoclase felspar will often show this difference of extinction position and also of

polarisation colour, one area showing yellow and the other grey. These peculiarities are indicative of twinning, and often afford a useful means of distinction between different minerals. The reason for the different positions of extinction of the two areas is to be found in the fact that, as they have different crystallographic orientations, their rectangular vibration directions are not parallel, each to each. The reason for the difference of polarisation colour is to be found also in the fact that the two areas have different crystallographic orientations; they behave just as if they were two separate sections of the same mineral. This particular kind of twinning, resulting in the production of two such areas only, is known as simple twinning.

Another type of twinning is shown by sections of plagioclase felspars such as labradorite. In this case there are not merely two such areas, but any number from three upwards in one crystal. When one of these fragments is examined between crossed nicols, it shows alternating black and illuminated ribbons when one set is in extinction. It is worth noting that alternate ribbons extinguish simultaneously. This particular type of twinning, of which labradorite has been taken as an example, is known as lamellar twinning.

The fact that twinning is exhibited commonly by some minerals and never in others, renders this particular character very useful in mineral identification. Simple twinning serves to distinguish

orthoclase felspar from quartz, and from plagioclase felspar—which shows lamellar twinning.

It is obvious that this test of twinning, the different positions of extinction, can only be observed in the case of anisotropic sections. This particular kind of evidence is not available in the case of minerals crystallising in the cubic system, and it is therefore a matter of some difficulty to prove the presence of twinning in sections of minerals having such a high degree of symmetry. Some indication, however, is sometimes given by a re-entrant angle, though this is not a satisfactory proof of twinning.

Zoning.—The zoning of such crystals as those belonging to the Albite-Anorthite series has already been mentioned, and it has been pointed out that this particular character may be observed in ordinary light in consequence of the fact that the different shells have unequal refractive indices and possibly different degrees of alteration. But this zoning is often quite inconspicuous until the examination is made between crossed nicols. As each zone has its own position of extinction, the structure is still more conspicuous in this condition of the microscope, notwithstanding the fact that the same crystal may show lamellar twinning. Pyroxenes also may exhibit zoning between crossed nicols, even in cases where such a character was invisible in ordinary light.

Anomalous Double Refraction.—It has been seen that all sections of minerals crystallising in the cubic system, ought, when examined between

crossed nicols, to be isotropic; but many sections of the mineral leucite (usually considered to crystallise in this system) show grey polarisation colours in intersecting ribbons.

The " anomaly " is that a cubic mineral is anisotropic, and that anomaly is bound to exist as long as we regard the mineral as belonging to this system. The mineral is not really a cubic mineral, but its crystals have a symmetry which is so nearly that of the trapezohedron, that it is a matter of some difficulty to place it elsewhere. Some sections of garnet exhibit similar anomalies.

Aggregate Polarisation.—This phenomenon of aggregate polarisation is seen in those cases where a mineral has been decomposed with the production of an aggregate of smaller, anisotropic fragments of some other mineral or minerals. The alteration product is made up of small fragments with all possible orientations, and consequently there is never complete extinction of the pseudomorph—a fact which occasionally troubles students. If such a pseudomorph be looked upon as a crowd of small individuals, the difficulty disappears.

Determination of Polarisation Colour.—Up to the present we have used the wedge merely to demonstrate the effects of variation in thickness of an anisotropic section. We have now to consider some other uses to which it may be put.

It has been suggested that, by practice, the student may acquire the ability to recognise the particular order in which any mineral fragment is

polarising, merely by inspection; but the wedge may be used to place the matter beyond doubt. In order to demonstrate the method, a fairly large fragment of a doubly refracting mineral in thin section should be placed between crossed nicols, and the stage rotated until it occupies one of the positions where the polarisation colour is at its brightest; the mounted wedge should then be inserted into the slot of the eye-piece until it occupies a position immediately above the fragment to be examined. In such circumstances the polarisation effect is due partly to the mineral on the stage, and partly to the wedge in the slot. There are two possible cases:—

(1) The effect of the two is as the sum of two quantities having the same sign — the polarisation colours of the two are higher in the scale than either alone.

(2) The effect of the two is as the sum of two quantities having unlike signs — the polarisation colours of the two are lower in the scale than either alone.

It is the second case that we require; a rotation of the stage through 90° will convert case (1) into case (2). Having obtained the required opposition between section and wedge, it will be seen that at some position in the latter, a black band takes the place of one of the colour-bands in the scale; the particular band of colour replaced by this compensation band is the polarisation colour of the mineral plate. If the mineral plate whose polarisa-

tion colour we set out to determine is the only frag-
ment in the slide, or if it is at the edge of a rock
section, the fact may be demonstrated by placing
the section in such a position that it is only covered
by one side of the wedge. On this side, the com-
pensation band will be obtained; on the other, the
ordinary scale will be exhibited; and the com-
pensation band will be continuous across the
wedge with the colour which is that exhibited by
the section alone.

The test may be applied to any anisotropic
section, though in the case of a small fragment, or
one of irregular thickness, a little care is necessary
in making the determination.

Sign of Dimetric Minerals.—We have already
seen that a section of quartz cut parallel to the
principal crystallographic axis *c*, polarised in
yellow of the first order, the highest polarisation
colour possible in sections of quartz of the standard
thickness. All minerals crystallising in the
hexagonal and tetragonal systems (dimetric) are
similar in this respect, that, although the highest
possible polarisation colour for any mineral is a
function of the birefringence, they all exhibit their
highest polarisation colour when cut in such a
direction that the crystallographic axis *c* lies in
the plane of section. This means that, for such a
section, the difference in velocity of the two rays
penetrating it, is at its maximum; and as such
sections show straight extinction, the two vibration
directions are respectively parallel to and per-
pendicular to the length of the crystal. These

particular directions, being the vibration directions
of the rays with the two extremes of velocity for
the crystal, are known as ether axes; that of the
fastest ray is referred to as the X ether axis, and that
of the slowest ray as the Z ether axis.

There are two cases:—

  Where *c* coincides with Z, the double
      refraction is positive.

  Where *c* coincides with X, the double
      refraction is negative.
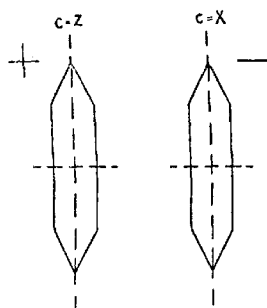
Dimetric crystals.
20. Positive.   21. Negative.

The wedge may be used to determine which of
these two cases a particular vertical section of a
dimetric mineral represents.

Before this can be done, however, it is necessary
to learn something more about the wedge. We
know that its two vibration directions are
respectively parallel and perpendicular to the
length, but we have not yet determined which of

these is "fast" and which "slow." In order to
make this determination, we require a vertical
section of a dimetric mineral whose sign is known.
A small crystal of quartz meets our requirements
admirably; it is well known that quartz is positive,
therefore in a vertical section the length is the
direction of slow vibration.

The section is placed on the stage between
crossed nicols and brought to a position of
maximum illumination, and the wedge inserted
into the eye-piece slot. Opposition between crystal
and wedge might be obtained with the crystal either
N.E : S.W., or N.W : S.E.   Suppose that oppo-
sition is obtained when the *c* axis is N.E : S.W.,
the length of the wedge being N.W : S.E.
We know that *c* is slow, and that *a* is fast, and
as opposition is taking place, the ray that came
quickly through the quartz crystal comes slowly
through the wedge, and vice versa. Therefore, the
light vibrating parallel to the length of the wedge
is penetrating slowly, the light vibrating per-
pendicular to the length is penetrating more
rapidly.

We have thus determined the character of our
wedge, and can speak of it as a slow wedge in
terms of the kind of ray vibrating longitudinally.
This fact having been determined, the knowledge
thus obtained may be applied in order to determine
the sign of any vertical section of a dimetric
mineral.

Apatite, for instance, is elongated along the axis
c. A section parallel to *c*, tested with the wedge

between crossed nicols, is seen to give compensation with its length N.W:S.E.
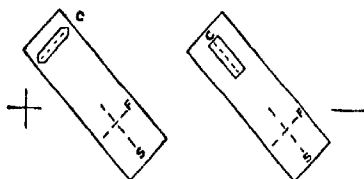
Positions of crystals giving compensation with the slow wedge.
22. Positive.   23. Negative.

As wedge and crystal must be in opposition, and as we know that the length of the wedge is " slow," then the length of the apatite must be " fast," $c =$ X and the sign is negative.   The test may be applied to any vertical section of a dimetric mineral if we know the position of the crystallographic axis c in the section.

Optic Orientation of Trimetric Minerals.—It has been seen in the foregoing account of dimetric crystals—

  i.   That in any anisotropic section there are two vibration directions which are perpendicular;

 ii.   That the two rays penetrating such a section are propagated with different velocities;

iii.   That in a section containing the crystallographic axis c, the difference of velocity (indicated by the polarisation colour) is at a maximum;

iv. That in such a section the vibration
directions are respectively parallel to
and perpendicular to the crystallo-
graphic axis *c*;

v. That the vibration directions giving
extremes of velocity are known as ether
axes;

vi. That the sign of the double refraction may
be determined by use of the wedge.

It will be seen that in a dimetric crystal there are
many possible sections parallel to *c*, but all these
have the same polarisation colours, and hence each
contains two ether axes. We have to regard such
a crystal as having, one ether axis coinciding with
the crystallographic axis *c*, and an infinite number
of other ether axes lying in a horizontal plane. In
the case of the orthorhombic system, however, such
is not the case. It is found that a section contain-
ing the *a* and *c* crystallographic axes (the brachy-
pinacoid, 010) polarises in colours different from,
and sometimes very much different from, those
given by the section containing *b* and *c* (the macro-
pinacoid 100). It is also found that the section
perpendicular to *c* (the basal pinacoid, 001), is not
isotropic.

Clearly there are some striking differences be-
tween the optical properties of a dimetric mineral
and those of an orthorhombic mineral; the two
ether axes X and Z, however, still coincide with two
crystallographic axes, and it is our object to deter-
mine with which of the three crystallographic axes
these ether axes coincide. The remaining crys-

tallographic axis, although it is merely the vibration direction of a ray which has some intermediate velocity (not necessarily a mean), is regarded as an ether axis, and is represented by the letter Y.

There are six possible cases within the system :—

1.	2.	3.	4.	5.	6.
$a=X$	$a=X$	$a=Y$	$a=Y$	$a=Z$	$a=Z$
$b=Y$	$b=Z$	$b=X$	$b=Z$	$b=X$	$b=Y$
$c=Z$	$c=Y$	$c=Z$	$c=X$	$c=Y$	$c=X$

The particular case represented by any orthorhombic crystal may be determined if we have three sections parallel to the three pinacoids. Barytes supplies us with a suitable case; fragments are fairly easy to prepare; it is important, however, that the sections should be as nearly as possible parallel to the three pinacoids.
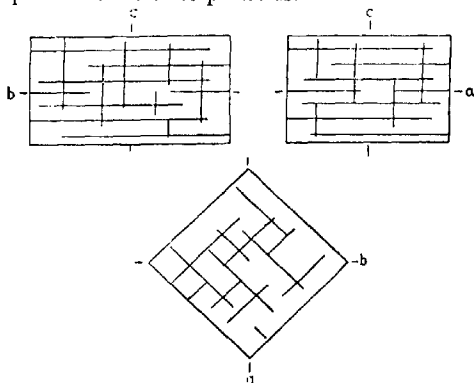
Pinacoidal sections of barytes.
Macropinacoid. 25. Brachypinacoid.
26. Basal pinacoid.

By determining the positions of extinction in the three sections, it is found that their vibration directions are, in Figures 24 and 25, parallel to the two cleavages (basal and prismatic, the former being the more perfect), and in Figure 26 that they bisect the cleavage angles; it is also found that they coincide with the crystallographic axes.

Each section should be taken in turn, rotated to a position of maximum illumination, and tested with the slow wedge, in two such positions if necessary, to find the position of compensation.

It is found that—

 In section i., in position of compensation, c is parallel to the length of wedge. ∴ c is " faster " than b.

 In section ii., in position of compensation, c is parallel to length of wedge. ∴ c is " faster " than a.

 In section iii., in position of compensation, b is parallel to length of wedge. ∴ b is " faster " than a.

Hence it follows that—

$$c > b > a$$
$$\&\quad a = Z$$
$$b = Y$$
$$c = X$$

Careful testing with the wedge will demonstrate that, of the three sections, ii. shows the highest polarisation colours—a further proof that that is the section containing the ether axes with the maximum velocity difference, X and Z. Of the other two sections, iii. exhibits polarisation colours almost as

high as those of ii., very different from those of i.—
a demonstration, if such be required, that the
velocity of the ray vibrating in Y is not a mean
between the two extremes.

The sign of double refraction cannot be obtained
with certainty without the use of convergent
polarised light.

The three ether axes, X, Y and Z, exist in all three
trimetric systems, that is, the orthorhombic, mono-
clinic, and triclinic. In the last two systems, how-
ever, as the crystallographic axes are not, and as
the ether axes are always, at right angles, the two
kinds of axes cannot coincide. In the monoclinic
system, the *b* crystallographic axis is coincident
with one of the ether axes (X, Y, or Z), while the
remaining two lie in the plane of symmetry. The
situation of those two may be ascertained by
measuring the extinction in a section parallel to the
plane of symmetry (the clinopinacoid, 010).
Neither of these ether axes necessarily coincides
with either the crystallographic axis *a* or *c*.

The symmetry of the triclinic system being so
low, it would be profitless to attempt a statement of
optic orientation.

In the foregoing statement of optic orientation,
we have considered only those sections containing
two ether axes. Other sections have been ignored
as introducing unnecessary difficulty at the present
stage. It is quite evident that, as a section may
take any direction whatever through a crystal, only
a few of these will contain two ether axes; some will
contain one only, while in the majority of cases the

section will not contain any. Nearly all these, however, are doubly refracting, and must therefore contain two vibration directions. A full statement of the case may be postponed for the present, but it may be pointed out that—

> In sections containing two ether axes, vibration takes place parallel to them.
>
> In sections containing one ether axis only, the vibration directions are respectively parallel to and perpendicular to this direction.

CHARACTERS OF MINERALS BETWEEN CROSSED NICOLS IN CONVERGENT LIGHT

IN considering the examination of transparent mineral plates, it has already been seen that there are three conditions of the microscope, all of which must be used in turn if we are to acquire a satisfactory amount of information in regard to the minerals in thin section. Even after this examination, it is not always possible to say with certainty that a particular mineral has been satisfactorily identified. The need for some further information is sometimes keenly felt. Convergent polarised light often supplies us with a means of acquiring the required information.

Methods of Obtaining an Interference Figure.— In fitting up the microscope, the instrument is first arranged as for use with parallel polarised light. The high power objective (usually $\frac{1}{4}$in.) must be used. A system of converging lenses is fitted either beneath the stage or above the polariser, and a lens (the Bertrand lens) is placed in the tube of the microscope, either sliding in by means of a slot or fixed to the lower end of a draw tube. It is necessary to point out that some of these adjustments must be made with care, as the best results are not always obtained. Students should be quite sure that the nicols are in use and crossed, that the

51

mirror is adjusted to give the best possible illumination, that the Bertrand lens is in position, and that the converging lenses occupy their place between polariser and stage.

The effect may often be further improved by adjusting the objective and the converging system to the best advantage. The interference figure obtained in these circumstances with suitable sections of doubly refracting minerals is the best obtainable; but although the Bertrand lens is a necessity if determinations of sign are to be made, it is not absolutely necessary in order to obtain a view of the figure.

If all the adjustments here described, with the exception of the insertion of the Bertrand lens, have been effected, the figure may be focussed by means of an ordinary pocket lens held a little way (usually between 1in. and 3in.) above the eyepiece. The figure may also be observed without the Bertrand lens if the eyepiece also is removed.

It is sometimes useful to know the last two methods, because, although the figure obtained is not so large as that obtained with the Bertrand lens, it is perhaps rather more clear. In the following description, however, it will be assumed that the lens is in use.

Uniaxial and Biaxial Interference Figures.—The interference figure is seen when a suitable section of a doubly refracting mineral is examined in convergent light, and is one of two types. One of these is obtained when a basal section of a dimetric mineral is examined; the other when the section is
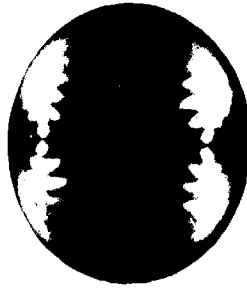
PLATE I
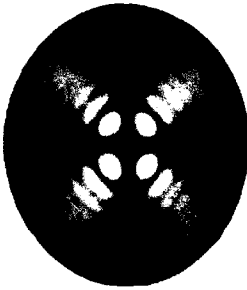
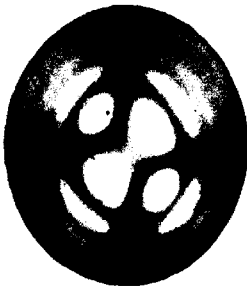1.- Uniaxial interference figure.

2. Uniaxial interference figure.
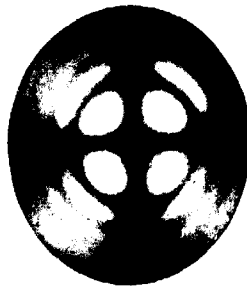Mica plate introduced.

3.—Biaxial interference figure. Oblique
position.

4. Biaxial interference figure.
Straight position.

5.—Pseudo uniaxial interference figure.
Oblique position.

6. -Pseudo-uniaxial interference figure.
Straight position.

To face page 52.

cut from a trimetric mineral perpendicular to the
X or Z ether axis.

It has been seen that, in general, when light is
transmitted through a section of a doubly refracting
mineral, it is split up into two rays having different
velocities. There are sections of such minerals,
however, perpendicular to which light is trans-
mitted with one velocity only. These directions of
propagation are known as optic axes. Dimetric
crystals have one such direction, which coincides
with the *c* crystallographic axis; they are hence
referred to as *uniaxial*. Trimetric crystals have
two such directions, and are consequently referred
to as *biaxial*. It is always the case that these two
optic axes lie in a plane which contains also the X
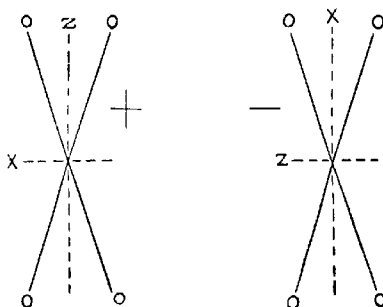
Optic axes and ether axes in biaxial crystals.
27. Positive.   28. Negative.

and Z ether axes, and that they are situated
symmetrically with regard to them; that is, X and
Z bisect the angles between the optic axes.

There are two cases—
  i. Z bisects the acute angle: double refraction positive.
  ii. X bisects the acute angle: double refraction negative.

In either case Y is perpendicular to the plane containing the optic axes (the optic axial plane) and is known as the optic normal.

The complete uniaxial interference figure is obtained when the section is perpendicular to the optic axis. It consists, as a rule, of a series of concentric circles which give Newton's scale of colours; the succession of colours when traced from the centre outwards is the same as that previously obtained with the wedge, commencing with the thin end. This system of rings is traversed by a black cross (N.S : E.W.) the arms of which intersect at the centre. The figure remains unchanged as the stage is rotated.

The complete biaxial interference figure is obtained when the section is perpendicular to the acute bisectrix. It consists of a similar succession of colours, but in general in this case, they surround two centres. Travelling outwards from these centres it is seen that the two sets of rings fuse to form lemniscates, which ultimately give place to ellipses. The system of rings is traversed by black bands, but in this case there is a striking change as the stage is rotated. There is always a black band traversing each "eye"; the bands form a cross when the trace of the optic axial plane (the line joining the two eyes) is situated N.S. or E.W. When that

line is situated N.E :S.W. or N.W :S.E., the cross has split into hyperbolæ, one traversing each eye.

It is instructive to study the effects of variation in thickness in the case of minerals showing the two types of figure. This can be done conveniently in the case of minerals which have a good cleavage in the direction of section, such as the two micas, phlogopite and muscovite. Phlogopite is not an ideal case, but it is convenient; it shows a figure which is only approximately uniaxial, though the approximation is usually sufficiently close. A cleavage flake which is fairly thick should be selected and placed (unmounted) on the stage. If the section is thin enough to transmit the light, a uniaxial interference figure with several rings will be seen. Successive observations should be made on thinner and thinner flakes, and it will be seen that the number of rings in the field decreases until the final stage is reached with the innermost ring outside the field. The black cross, however, persists.

Muscovite supplies us with an almost perfect example of a biaxial interference figure. The process of examining progressively thinner flakes should be repeated, preferably with the figure in an oblique position. It is found that the rings expand around the eyes until even the innermost ring has given place to a lemniscate or an ellipse, or has even disappeared beyond the limits of the field. Here again the hyperbolæ persist throughout in the same position.

A similar change is observed if a series of minerals is examined in section (the sections should

be of a constant thickness) commencing with one having a high double refraction and proceeding to those with lower and lower double refraction. A similar expansion is observed analogous in the case of uniaxial minerals, to the thinning of biotite, and in the case of biaxial minerals to the thinning of muscovite.

An examination of a biaxial series also demonstrates the fact that in some cases the eyes come nearer together than in others; the distance between them being roughly a measure of the optic axial angle (the acute angle). This variation in the value of the optic axial angle would seem to suggest that there is no reason to suppose that there is any sharp distinction between uniaxial and biaxial minerals; the former may be regarded as a special case of the latter, where the optic axial angle has become so small as to be difficult to measure. Biotite or phlogopite is an example of a mineral which is certainly biaxial, because, as the stage is rotated, the black cross is seen to split up into hyperbolæ; but the optic axial angle is so small that the figure never shows two eyes even in thick sections.

Sign of Uniaxial Minerals.—It is not necessary that a mineral section which has been prepared specially to give an interference figure should have the same thickness as an ordinary rock section, in fact, it is only in the case of minerals with a very high double refraction that such a thin section gives the best results. As a rule, minerals in thin section, when examined in convergent polarised light, exhibit no coloured rings, but only a black

cross or hyperbolæ. Students must be prepared, then, to find that the figures to be examined will be very variable as to the number of coloured rings in the field. Even supposing the thickness to be constant, the number of rings in the field will, as has been seen, be dependent on the birefringence.

Fortunately, however, there is one method which can be used in order to determine the sign of any uniaxial mineral showing a complete figure. That method involves the use of a mica plate. This is a small rectangular flake of muscovite, usually cut in such a way that its slow vibration direction is parallel to the length of the rectangle. It should be mounted on a glass slip $\frac{1}{2}$in. in width. The figure having been obtained, the mica plate should be inserted into the slot immediately above the objective. It has the effect of producing expansion in one pair of opposite quadrants, and contraction in the other pair. Where expansion takes place, two black spots appear near the centre of the field. There are two cases.
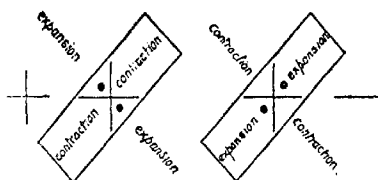
Sign of uniaxial minerals with mica plate.
29. Positive.   30. Negative.

When the double refraction is positive, a straight

line joining the two spots would lie perpendicular to the length of the plate, and when negative, parallel to the length.

The same method may be used in order to determine the sign of a biaxial mineral (such as biotite) with small optic axial angle.

Sign of Biaxial Minerals.—Having obtained the figure, the stage should be turned so that the trace of the optic axial plane occupies an oblique position (say N.E. :S.W.). The converging apparatus should be removed and the section examined in parallel polarised light by means of the low power objective. Testing with the wedge, the stage remaining in the same position, will give either compensation, or will raise the polarisation colours.

If compensation is obtained with the optic axial plane N.E. :S.W. using a slow wedge, then, as the

length of the wedge is parallel to the optic normal, that direction must be the vibration direction of the faster ray, and the trace of the optic axial plane must be that of the slower; but the latter is

31. Compensation with a slow wedge for a negative biaxial crystal.

the direction of the obtuse bisectrix, since the section is cut perpendicular to the acute bisectrix. Then Y (the optic normal)>obtuse bisectrix, that is, the obtuse bisectrix=Z. The acute bisectrix must therefore be X, and the double refraction is negative.

When the double refraction is positive, compensation is obtained when the slow wedge is inserted parallel to the trace of the optic axial plane.

It is possible to determine the sign of a mineral showing a biaxial figure without removing the converging apparatus. The wedge or mica plate should be inserted into the lower slot while the figure (with the optic axial plane N.W.:S.E. or N.E:S.W.) is carefully observed. There will be one of two effects. Either the rings will become lemniscates or the lemniscates will become rings. In the first case opposition is taking place; in the second case, coincidence. The sign may be determined by a process of reasoning similar to that described for the preceding method.

Partial Interference Figures. — A complete uniaxial interference figure is given only by a section which is perpendicular to the vertical axis of a dimetric crystal (the optic axis); but as only a small minority of the fragments in a rock section are cut in that direction, it is desirable to have some method of determining the sign of double refraction of a mineral when the section has some other orientation.

The appearance of the partial interference figure depends largely on the obliquity of the section examined. In the case of a section which is almost perpendicular to the optic axis, the centre of the figure may be in the field of the microscope, but will not coincide with the centre of the field; rotation of the stage causes the centre of the figure to describe a circle concentric with that limiting the field. In

such a case the sign may be obtained by using a mica plate as with a complete figure.

A section departing still further from the position of that giving a complete figure may show only a portion of the system of rings on the margin of the field, or these may be entirely outside its limits, but in any case the arms of the black cross will sweep across the field as rotation takes place. The movement of these arms must be observed if the sign is to be determined.

Let it be supposed that the centre of the figure is somewhere outside the field away towards the N.E. On rotation of the stage in the clockwise direction, a horizontal arm sweeps across the field from N. to S., then a vertical arm from E. to W., then a horizontal arm from S. to N., and immediately before a complete rotation has taken place, a vertical arm from W. to E. The succession of events may be illustrated by holding two penholders at right angles to form a cross, resting a coin on the table, and, with the centre of the cross, describing a circle of greater diameter than that of the coin but concentric with it, so that the arms of the cross, while retaining their N.S. and E.W. directions, sweep in turn over the coin. It will be seen, then, that it is possible to locate the centre of the figure after a rotation of the stage has been completed.

The centre of the figure should be placed so that a straight line joining it with the centre of the field bisects one of the angles formed by the cross-wires, say to the N.E. Having got that in position, re-move the converging apparatus and examine in

parallel polarised light between crossed nicols with
the low power objective. Test with the slow
wedge, on the assumption that the straight line
joining the two centres (field and figure) is the ver-
tical axis *c*.
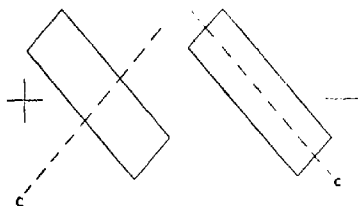
Compensation with a slow wedge and uniaxial crystals.
32. Positive.   33. Negative.

The wedge being inserted in a N.W. : S.E. direc-
tion, compensation in that position indicates posi-
tive double refraction, because $c = Z$. If compen-
sation is obtained with the centre of the figure in
the N.W. : S.E. line, the double refraction is
negative, because $c = X$.

The sign of a mineral in section showing only a
partial biaxial figure can only be obtained by means
of more complex methods.

In applying the test of convergent polarised light
to a doubly refracting mineral in thin section, the
information desired is :—

    i. Is the mineral uniaxial or biaxial?

    ii. What is the sign of its double refraction?

One of the difficulties encountered is that the sec-
tion is probably too thin to show anything of the
coloured rings, but the " brushes " ought always to

be visible in a well-selected crystal. As a rule the fragment chosen should be the one giving the lowest polarisation colours. A black cross which remains unbroken on rotation, or vertical and horizontal brushes sweeping across the field, indicate a uniaxial mineral. A black cross breaking up into hyperbolæ, or a brush which at times occupies an oblique position in the field, indicates a biaxial mineral. It is worth noting that a section of a biaxial mineral, cut perpendicular to one of the optic axes, shows a system of concentric coloured circles traversed by only one black brush, the two ends of which, on rotation of the stage clockwise, follow the margins of the field in the anti-clockwise direction. The movements of that brush are of considerable importance in the examination of thin sections.

After the determination of the kind of figure, the sign of the double refraction should be obtained. This may be done in all cases where a complete figure is exhibited, and in the case of a uniaxial mineral, even where only a partial figure is seen.

PLATE II
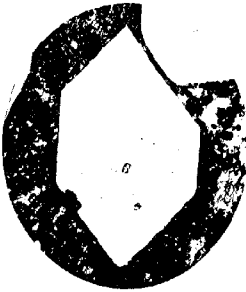
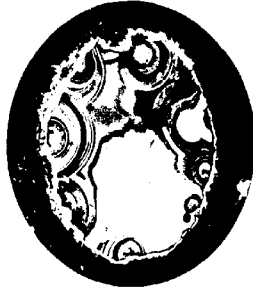
1.—Quartz. Ordinary Light. Vertical
section. Showing Form.
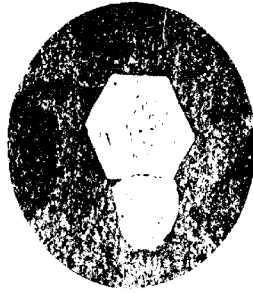
2- Quartz. Ordinary Light. Basal
section. Showing form.

3.—Quartz. Ordinary Light. Showing
corrosion.

4. Quartz. Ordinary Light. Showing
corrosion

5.—Chalcedony in amygdule.
Ordinary Light.

DESCRIPTIONS OF COMMON ROCK-FORMING MINERALS

FORMS OF SILICA

Quartz.—SiO_2. *Hexagonal. Birefringence positive.*

Colour.	None.
Form.	Commonly allotriomorphic, but occasionally showing hexagonal outlines.
Cleavage.	None.
Ref. Index.	1·55. A little higher than that of Canada balsam.
Alteration.	None.
Inclusions.	Minute liquid and gas inclusions sometimes seen with $\frac{1}{4}''$ objective.
Pol. Colours.	1st order. Basal sections isotropic.
Twinning.	Not seen.

It will be seen that the majority of the characters are negative; there is never any colour, cleavage, or alteration, twinning is not visible, there is rarely any form, and the refractive index is not such as to give any high relief. The absence of definite characters is the fact to be borne in mind by the student.

Tridymite	SiO_2. A rare variety of silica usually occurring as nests of scale-like crystals.
Chalcedony	SiO_2. A secondary form of silica found filling cavities. Usually in pale shades of brown, showing concentric arrangement. Between crossed nicols, shows a very characteristic aggregate polarisation, with black crosses due to radiating crystals.
Opal	SiO_2,nH_2O. Also occurs filling interstices, and much like chalcedony in ordinary light, but distinguished by its isotropism between crossed nicols.

63

FELSPARS

Orthoclase.

Plagioclase.

Microcline.

Albite-Anorthite Series.

The common felspars are silicates of aluminium with potassium, sodium, or calcium. Orthoclase felspar crystallises in the monoclinic system; the plagioclase felspars crystallise in the triclinic system. All possess cleavages parallel to oo1 (basal pinacoid), and o1o (clinopinacoid or brachy-pinacoid).

Orthoclase.—$KAlSi_3O_8$. *Monoclinic.*

Twinning.	*Manebach. Twin plane* 001 (*basal pinacoid*).		
	Baveno.	,, ,,	021 (*clinodome*).
	Carlsbad.	,, ,,	100 (*orthopinacoid*)
	,, *Comp.*	,,	010 (*clinopinacoid*).

Birefringence negative.

|	
Colour.	None.
Form.	Sometimes idiomorphic, when rectangular or hexagonal sections are shown. Often allotrio-morphic.
Cleavage.	In favourable sections two rectangular cleav ages are seen, but some sections show one cleavage only; other sections show no cleavage.
Ref. Index.	1·52. Slightly less than, but very near to, that of Canada balsam.
Alteration.	Often turbid in consequence of alteration, but may be quite or partially transparent.
Pol. Colours.	1st order; greys, white, and yellow.
Extinction.	Commonly oblique, but sometimes straight.
Twinning.	Absent or simple.

PLATE III
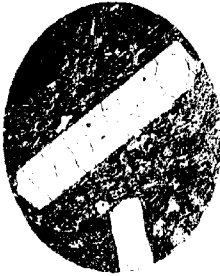
1. -Orthoclase. Ordinary Light.
Showing form.
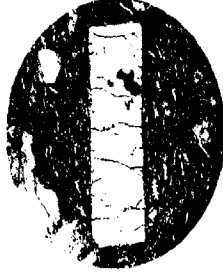
2. Orthoclase. Ordinary Light.
Showing form.
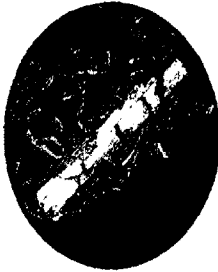
3. -Orthoclase. Crossed nicols.
Showing cleavages.

4. Orthoclase. Ord. L. Showing altera
tion and intergrowth with quartz.

5. Orthoclase. Crossed nicols Showing
Carlsbad twinning.
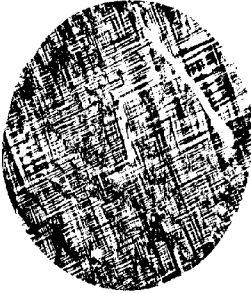

6. Orthoclase. Crossed nicols. Showing
Baveno twinning.

PLATE IV

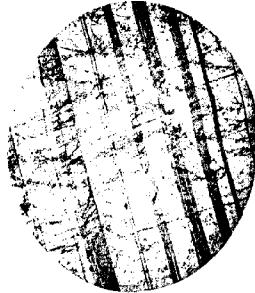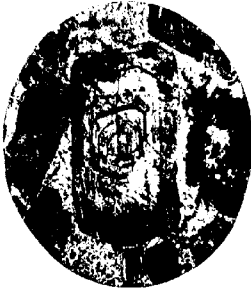1.—Microcline. Crossed nicols. Showing
cross-hatching.

2. -Plagioclase, ab.-an. ser. Crossed nicols.
Showing lamellar twinning,

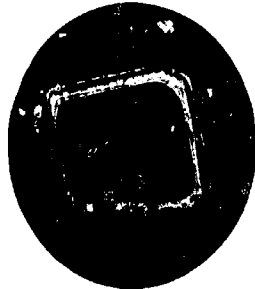
3. Plagioclase, ab-an ser. Ordinary Light.
Showing zoning by alteration.

4.—Plagioclase, ab.-an. ser. Crossed
nicols. Showing lamellar twinning.

5. Plagioclase, ab.-an ser. Ord. L.
Showing zoning by inclusions

6. - The same. Crossed nicols. Showing
zoning and lamellar twinning.

Microcline.—$KAlSi_3O_8$. *Triclinic.* *Birefringence negative.*

This mineral cannot be distinguished in ordinary light from orthoclase, but between crossed nicols it shows lamellar twinning in two directions, the two sets often intersecting at angles approaching 90°. The pattern produced is that known as cross-hatching.

Albite-Anorthite Series.—*Triclinic. Twin plane* 010 (*brachypinacoid*).

The minerals in this series form an isomorphous group, with albite and anorthite at the two extremes. The members of the series cannot be said to have any well-defined individuality, as the several mineral names do not imply any definite composition.

The composition range of the several members of the series is illustrated below, where the albite molecule (Ab) $NaAlSi_3O_8$, and the anorthite molecule (An) $CaAl_2Si_2O_8$, are combined in the various proportions.

|	Ab.	An.	Ref. Index.
Albite	10	0	1·53
	9	1	
Oligoclase	8	2	1·54
	7	3	
Andesine	6	4	1·55
	5	5	
Labradorite	4	6	1·56
	3	7	
Bytownite	2	8	1·57
Anorthite	1	9	
	0	10	1·58

An inspection of the above table will show that labradorite, for example, may have as little as 25% Ab. or as much as 50% Ab.

The members of this Ab. An. series are distinguished from orthoclase by the lamellar twinning seen when examined between crossed nicols. It is desirable also to distinguish between the different members of the series, but the distinction is a matter of some difficulty. The most commonly accepted method is based on the extinction angle, as measured from the twin striations, the extinction angle being greatest at the Anorthite end of the series. The beginner, however, is recommended to remain satisfied with having recognised the mineral as plagioclase felspar (Ab. An. series). He can later make himself familiar with the method of extinction or make use of the variation in refractive index. It will be seen that the refractive index of oligoclase is equal to that of Canada balsam. If the refractive index is less than 1·54 the felspar may be called albite; if greater than 1·54, the degree of relief may be used as a means of getting the approximate place of the felspar in the series.

Resemblances.—The distinction between orthoclase, microcline, and the Ab. An. series, is easily effected by a consideration of the kind of twinning. Quartz, however, is not always easy to distinguish from orthoclase. In difficult cases a careful search should be made for cleavage, alteration, and twinning. The presence of any one of these would eliminate quartz. The distinction may also be effected in convergent light; quartz is uniaxial, and orthoclase biaxial.

PLATE V
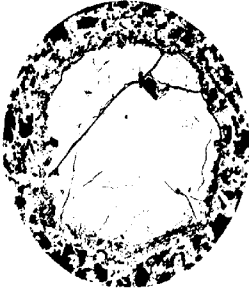
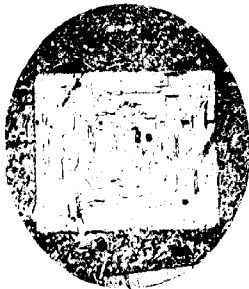1.—Leucite. Ordinary Light. Showing form.

2.—The same. Crossed nicols. Showing cross-hatching.

3.—Leucite. Ordinary Light. Showing inclusions.

4.—Nosean. Ordinary Light. Showing zoning.

5.—Nepheline. Ordinary Light. Showing form of vertical section.

6.—Nepheline. Ordinary Light. Showing form of basal sections.

FELSPATHOIDS

Leucite.—$KAl(SiO_3)_2$. *Cubic* (?).

Colour.	None when fresh.
Form.	Sometimes octagonal, but usually rounded.
Cleavage.	None.
Ref. Index.	1.51. Sufficiently different from that of Canada balsam to have a fairly good relief.
Alteration.	May be quite fresh, but occasionally turbid and pale brown through alteration.
Inclusions.	Sometimes contains included fragments arranged radially or concentrically.
Pol. Colours.	May be quite isotropic, but often polarises in dark greys and shows intersecting twin lamellæ resembling those of microcline.

Resemblances.—May be confused with microcline, but it has a better relief in ordinary light, and a lower double refraction. Form is also useful.

Nosean.—*Silicate and sulphate of sodium and aluminium. Cubic. Cleavage 110 (Rhomb-dodecahedral).*

Colour.	None or brown.
Form.	Very variable. Often irregular, but sometimes showing hexagonal outlines.
Cleavage.	Occasionally, but not often, seen.
Ref. Index.	1.46. Has a good relief in consequence of its very low refractive index, but the common thick dark border is due to inclusions—not to refractive index.
Alteration.	To aggregates of zeolites—producing turbidity.
Inclusions.	Sometimes packed with dark brown inclusions, but often these are localised at the margins, giving a striking zoned appearance.
Pol. Colours.	Isotropic when fresh, but showing aggregate polarisation when decomposed.

Hauyne.—*Composition similar to that of nosean but with calcium silicate and sulphate in addition. Cubic.*

Often very similar to Nosean in appearance, but more commonly has inclusions localised at the centre, and sometimes shows blue or green colour.

Nepheline.—*Composition* $\begin{cases} m & NaAlSiO_4. \\ n & KAl(SiO_3)_2. \end{cases}$ *Hexa-gonal.   Cleavages prismatic and basal.   Birefringence negative.*

Colour.	None when fresh, but brownish when altered.
Form.	Rectangular or hexagonal.
Cleavage.	Rarely seen.
Ref. Index.	1·54. Very nearly equal to that of Canada balsam.
Alteration.	May be fresh, but often found decomposed to radiating aggregates of small acicular crystals.
Pol. Colours.	Basal sections isotropic; other sections polarising in greys (1st order).
Extinction.	Straight.
Twinning.	None.

Resemblances.—May be distinguished from felspars by its more common rectangular and hexagonal sections, its different type of alteration, its lower polarisation colours and isotropic sections, its straight extinction and the absence of twinning; also by examination in convergent light.

The allotriomorphic variety found in coarse-grained igneous rocks is known as Elæolite.

Sodalite.—*Silicate and chloride of sodium and aluminium.   Cubic.   Cleavage* 110 (*Rhomb-dodecahedral*).

|	
Colour.	None.
Form.	Allotriomorphic.
Cleavage.	Not always seen, but may be found in more than one direction.
Ref. Index.	1·48. Approximating to, but less than, that of Canada balsam.
Alteration.	Occasionally turbid through decomposition, but usually clear.
Polarisation.	Isotropic.

PLATE VI

1.—Muscovite. Ord. L. Showing
cleavage.

2. Muscovite. Ord. L. Showing cleavage
and intergrowth with biotite.
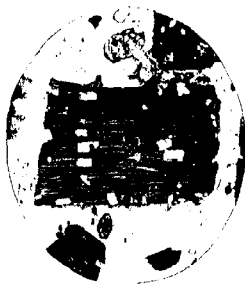
3. Biotite. Ord. L. Showing form,
cleavage and inclusions.

4. Biotite. Pol. L. Showing
apleochroism.

5.—Biotite. Ord. L. Showing partial
alteration to Chlorite.

6. Chlorite. Ord. L. Showing vermicular
habit and occurrence in amygdule.

MICAS

Characterised by their perfect basal cleavage and pseudo-hexagonal symmetry. Muscovite and Biotite are selected as examples of the group.

Muscovite.—*Comp.* $H_2KAl_3(SiO_4)_3$. *Monoclinic. Cleavage* 001. *(Basal). Birefringence negative.*

Colour.	None.
Form.	Allotriomorphic.
Cleavage.	One direction of cleavage nearly always seen.
Ref. Index.	1·58. No very striking relief, but still evidently much different from Canada balsam.
Alteration.	None.
Pleochroism.	Since the mineral is colourless in thin section, there cannot be any pleochroism; but occasionally it is found that around minute inclusions the mineral is a pale brown, and these haloes are pleochroic.
Pol. Colours.	Bright pinks and greens; sometimes low-order colours.
Extinction.	Straight.
Twinning.	None.

Resemblances. — Muscovite cannot easily be mistaken for any of the minerals previously described. Even ignoring other tests, the polarisation colours are usually sufficiently distinctive, though basal sections show very low colours.

Biotite. — *Comp.* $(K,H)_2(Mg,Fe)_2(Al,Fe)_2(SiO_4)_3$ *Monoclinic. Cleavage* 001 *(Basal). Birefringence negative.*

It has many characters in common with Muscovite, but differs in the following respects:—

Colour.	Brown.
Alteration.	Decomposes to a green product, Chlorite, which is sometimes pseudomorphous; but all stages in the alteration are to be seen.
Pleochroism.	Strong: from pale brown to dark brown.
Pol. Colours.	Commonly obscured by the absorption colour.

Resemblances.—The brown colour and pleochroism are sufficient to distinguish the mineral from any one of the preceding minerals.

OTHER MICACEOUS MINERALS

Chlorites.—*Basic silicates of iron, aluminium, and magnesium. Monoclinic. Cleavage* 001 (*Basal*).

Colour.	Green.
Form.	Usually as pseudomorphs after unstable ferro-magnesian silicates which contained alumina ; *e.g.*, biotite. Sometimes in parallel or radiating aggregates ; sometimes vermicular.
Cleavage.	In one direction only.
Ref. Index.	About 1.58.
Pleochroism.	Slight : pale green to darker green.
Pol. Colours.	1st order greys : often masked by absorption. Sometimes shows ultra-blues or ultra-browns.
Extinction.	Straight.

Chloritoids.—*Composition approximating to that of Chlorite. Monoclinic or Triclinic.*

Colour.	Indigo blue or greenish black.
Form.	Variable, but sometimes rectangular.
Cleavage.	One direction good : others obscure.
Ref. Index.	Variable, but always high.
Inclusions.	Abundant.
Pleochroism.	Usually from indigo blue to greenish yellow.
Pol. Colours.	1st order greys.
Extinction.	Usually oblique.
Twinning.	Common.

Resemblances.—Differ from Chlorites in having a high refractive index, often a curious indigo blue colour, and many inclusions. Pleochroism also is distinctive, usually from indigo blue to greenish yellow.

Talc.—$H_2Mg_3(SiO_3)_4$. *Monoclinic* (?).

Very much like Muscovite, but has a slightly lower refractive index, 1.56, and a little higher birefringence.

PYROXENES

The pyroxenes fall into a fairly well-defined group of minerals with a tendency to form crystals

PLATE VII

Ægirine, transverse section. Ordinary Light. Showing form and cleavages.

2.—Augite, vertical section. Ordinary Light. Showing form.

3. Augite, vertical section. Ordinary Light. Showing form and zoning.

4. Augite, trans. sect. Crossed nicols. Showing form, zoning and simple twinning

5. Augite. Crossed nicols. Showing zoning and "hour-glass" structure.

6. Enstatite, transverse section. Ordinary Light. Showing form and cleavages

with eight vertical faces, four of these being prism faces meeting at angles which are approximately 90°. All of them have prismatic cleavages which intersect at the prism angle. Composition, variable.

Monoclinic Pyroxenes

Augite.—*Silicate of calcium, iron, magnesium and aluminium. Monoclinic. Cleavage* 110 *(Prismatic). Twin plane* 100 *(Orthopinacoid). Birefringence positive.*

Colour.	Brown.
Form.	Transverse sections sometimes octagonal.
Cleavage.	In transverse sections, two at right angles. Other sections may show one only, or even none.
Ref. Index.	1·72. The mineral has a good relief and the cleavages and other cracks are conspicuous.
Alteration.	Sometimes to green chlorite, occasionally to hornblende.
Pleochroism.	Typically none : but some varieties show feeble pleochroism.
Pol. Colours.	Bright colours, commonly 2nd and 3rd order
Extinction.	Commonly oblique, but sometimes straight.
Twinning.	Simple and lamellar.

Diopside.—*Silicate of calcium, iron and magnesium.*

Differs from Augite only as regards colour—it is green or colourless instead of brown.

Aegirine.—*Silicate of sodium and iron.*

Sections of this pyroxene are also green, but, as the mineral is strongly pleochroic, the different fragments seen in ordinary light exhibit different shades of green, ranging from blue green to yellow green—two extremes which are seen when the mineral is examined with the aid of the polariser.

Diallage.—*Similar to augite in composition.*

Distinguished by the possession of an extra

cleavage (pinacoidal) and by a fibrous, woody appearance when seen in ordinary transmitted light—due to the parallel arrangement of platy inclusions (schillerization).

Orthorhombic Pyroxenes

These form an isomorphous series, with Enstatite, $MgSiO_3$, birefringence positive, and Hypersthene $(Mg,Fe)SiO_3$, birefringence negative, at the two extremes. It is usual to recognise an intermediate member of the series in Bronzite.

They differ from Augite in having a lower refractive index (enstatite 1·67 and hypersthene 1·70), and also in their polarisation. 1st order colours are common, but hypersthene occasionally shows 2nd order colours. There is a tendency for the octagonal outline of transverse sections to become regular. Hypersthene also shows a peculiar pleochroism — blue-green to reddish brown, and sometimes schillerisation. Straight extinction is much more common than oblique extinction, the reverse of what is the case with the monoclinic pyroxenes.

AMPHIBOLES

As in the case of the pyroxenes, the amphiboles form an isomorphous series. In crystals of this group, however, only six vertical faces are usually found; the four prism faces meeting at angles of about 125° and 55°. The prismatic cleavages, of course, intersect at these angles. The amphiboles resemble the pyroxenes in many respects, not the least important being that of composition; and, in

PLATE VIII
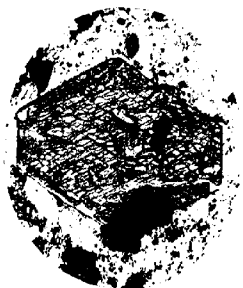
1.—Hornblende, transverse section. Ord L. Showing form and cleavages.

2.—Actinolite, transverse section. Ord. L. Showing form and cleavages.

3.—Hornblende, vertical section. Ord. L. Showing form and cleavage.

4.—Glaucophane, trans. sect. Ord. L. Showing form and cleavages.

5.—Hornblende, trans. sect. Ord. L. Showing alteration rim.

general, for any pyroxene, an amphibole can be found having the same empirical formula.

As there are many points of resemblance between the two groups, it is desirable to point out the characters by which we are enabled to distinguish between them; the most important are :—(1) the form, and (2) the cleavage angle.

Hornblende.—*Silicate of calcium, iron, magnesium, and aluminium. Monoclinic. Cleavage* 110 *(prismatic). Twin plane* 100 *(orthopinacoid). Birefringence negative.*

Colour.	Green or brown.
Form.	Transverse sections often show six-sided outline.
Cleavage.	Transverse sections show two intersecting at 125°.
Ref. Index.	1·65. Fairly good relief.
Alteration.	Not common, but occasionally pseudomorphed in magnetite or chlorite.
Pleochroism.	Strong : light to dark green, or light to dark brown.
Pol. Colours.	2nd order, but commonly masked by absorption colour.
Extinction.	Commonly slightly oblique; occasionally straight.
Twinning.	Occasional simple or lamellar twinning.

Actinolite.—*Silicate of calcium, iron and magnesium. Monoclinic.*

Distinguished from green hornblende by its paler green colour.

Tremolite.—*Silicate of calcium and magnesium. Monoclinic.*

Characterised by its entire freedom from colour.

Glaucophane.—*Silicate of sodium, aluminium, and magnesium. Monoclinic.*

Distinguished by its beautiful reddish or bluish-violet colour. In addition to either of these colours a pale greenish yellow is sometimes seen when the test for pleochroism is applied.

Anthophyllite.—(Mg,Fe)SiO$_3$. *Orthorhombic.*

A rather rare mineral which is distinguished from Hornblende by the fact that nearly all sections show straight extinction.

Resemblances of Amphiboles.—It is not always easy to distinguish between pyroxene and amphibole; but in cases of difficulty a careful search should be made for a characteristic outline or cleavage angle.

The only other preceding minerals at all likely to be confused with amphiboles are the Micas. Sections of biotite sometimes resemble hornblende fairly closely; and the difficulty is not minimised by the fact that the two minerals are often found in the same slide. The following will be found useful in making the distinction between the two minerals.

> Colour.—This test may be applied with advantage even though both minerals are pleochroic; the different fragments of the two minerals are not similarly coloured.
>
> Form.—Transverse sections of hornblende are easily recognisable when well-formed; it is the elongated longitudinal sections which cause trouble.
>
> Cleavage.—Transverse sections of hornblende again are easily distinguished from biotite by the possession of two cleavages meeting at 125°.

Ref. Index.—This test is useful, as biotite has
the lower refractive index.

Pleochroism.—A useful test is found in the fact
that biotite when showing the dark ex-
treme of pleochroism, often exhibits a
slightly mottled surface never seen in the
case of hornblende.

Extinction.—Biotite always shows straight ex-
tinction; hornblende sometimes shows
oblique extinction. Biotite, again, shows
the mottled surface when in extinction.

Tremolite is sometimes difficult to distinguish
from muscovite, but careful search should be made
for the two cleavages and for oblique extinction,
either of which will rule out muscovite.

OLIVINES

Olivine. — $(Mg,Fe)_2SiO_4$. *Orthorhombic. Bire-
fringence positive.*

Colour.	None when fresh, but often associated with green serpentine.
Form.	When idiomorphic, shows hexagons which are irregular, but symmetrical about two of the diameters.
Cleavage.	Rarely seen, but irregular cracks frequent.
Ref. Index.	1·68. Good relief.
Alteration.	Commonly altered to green serpentine and black iron oxide. Alteration commences along the cracks and margins; these gradu-ally grow wider at the expense of the olivine until the final stage, a pseudomorph in ser-pentine, is reached.
Pol. Colours.	2nd and 3rd orders. Bright colours.
Twinning.	None.

Resemblances.—There is sometimes a difficulty in distinguishing between olivine and augite. Olivine may be distinguished by absence of colour, form (if idiomorphic), absence of cleavage, characteristic alteration.

Olivine is the intermediate member of an isomorphous group of minerals including :—

Forsterite—rich in magnesium. Mg_2SiO_4.
Olivine—
Fayalite—rich in iron. Fe_2SiO_4.

Forsterite is much like olivine, but decomposes to form a colourless serpentine.

Fayalite has a pale greenish colour and a slight pleochroism. Birefringence negative.

Serpentine.—*Hydrated silicate of magnesium and iron.*

It is easily recognised when associated with olivine or when a pseudomorph after well-formed crystals, but when it occurs as the bulk of large rock-masses, the sections present some difficulty to the beginner.

Colour.   Usually pale green or yellow in colour, or may be almost colourless.
Pleochroism. Occasionally distinct, but usually very feeble.
Pol. Colours. 1st order greys.

Resemblances.—Serpentine resembles Chalcedony to some extent, but has none of the radiating and concentric structure of that mineral. Chlorite may usually be distinguished by its cleavage or vermicular habit.
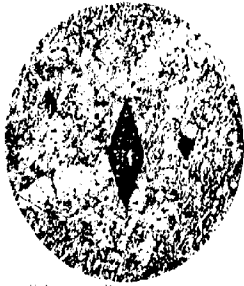
PLATE IX
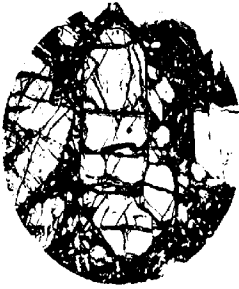
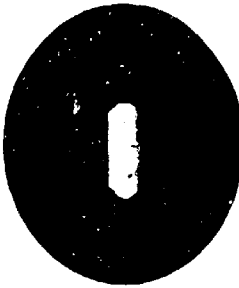1. Olivine. Ordinary Light. Showing form and alteration.

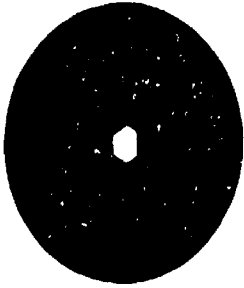2. Olivine. Ordinary Light. Showing form and more advanced alteration.

3. Serpentine. Ordinary Light. Pseudomorph after Olivine.

4. Sphene. Ordinary Light. Showing form and high refractive index.

5. Apatite, vertical section. Ord. L. Showing form and cleavage.

6. Apatite, basal section. Ordinary Light Showing form.

To face page 76.

Apatite.—$Ca(F,Cl)Ca_4(PO_4)_3$. *Hexagonal. Cleavage Basal. Birefringence negative.*

Colour.	None.
Form.	Transverse sections regular hexagons, vertical sections lath-shaped.
Cleavage.	Occasionally seen in vertical sections as transverse cracks.
Ref. Index.	1.64. Good relief.
Alteration.	None.
Pol. Colours.	1st order grey; basal sections isotropic.
Extinction.	Straight.
Twinning.	None.

Resemblances.—This mineral ought not to be mistaken for any of the foregoing; it is distinguished from nepheline by its refraction, and from olivine by its polarisation and form.

Sphene (Titanite).—*Silicate and titanate of calcium. Monoclinic. Twin plane 100 (orthopinacoid). Birefringence positive.*

Colour.	Yellowish-brown or greyish-brown.
Form.	Often lozenge-shaped—like an elongated ace of diamonds—but the form is not always well-developed.
Cleavage.	Rarely seen.
Ref. Index.	1.89. High relief and pitted surface.
Pleochroism.	Sometimes distinct, but usually feeble.
Pol. Colours.	High order greys. These, however, are so pale that the polarisation colour does not appear to be appreciably different from the absorption colour.
Twinning.	Not common, but sometimes simple twins are seen.

Resemblances.—When idiomorphic, no difficulty whatever is experienced, but other examples may exhibit some resemblance to augite. The differences of refraction and polarisation, however, should always serve to distinguish between them,

even when the obvious peculiarities of form are absent.

Garnets.—$R_3 R'''(SiO_4)_3$. *The Garnets form an isomorphous group of minerals which are here taken together for convenience.   Each is a silicate of at least two metals, one divalent and one trivalent, the positive elements represented in the group being calcium, magnesium, iron, manganese, aluminium and chromium. Cubic.*

Colour.	Pink, colourless, or brown.
Form.	Commonly rounded, but occasionally polygonal.
Cleavage.	Rarely seen, but irregular cracks are common.
Ref. Index.	1.76 to 1.83. Good relief.
Alteration.	None.
Inclusions.	Sometimes present in abundance.
Pleochroism.	None.
Pol. Colours.	Isotropic in nearly all cases.

Resemblances.—The isotropism will usually serve to distinguish garnet from any of the other highly refracting minerals in the preceding list.

Tourmaline. — *Boro-silicate of aluminium, with magnesium, iron and alkali metals.   Hexagonal. Birefringence negative.*

|	
Colour.	Commonly brown, but may be yellow, green, blue, or colourless. Often the colour is irregular in its distribution, different portions of a single fragment being differently coloured.
Form.	Transverse sections triangular or hexagonal. Vertical sections elongated, and even sometimes acicular. Often in irregular masses.
Cleavage.	None; but an imperfect basal fracture is sometimes seen in vertical sections.
Ref. Index.	1.63. Fairly good relief.

1.– Garnet (Melanite). Ordinary Light.
Showing form and zoning.
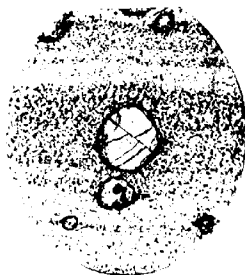
2. –Garnet. Ord. L. Showing rounded
form and high refractive index.
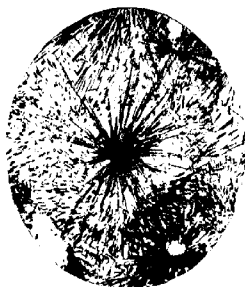
3. Tourmaline Ord. L. Showing
acicular and radiating habit.

Tourmaline, vert. section. Ordinary
Light. Showing form.

– Tourmaline, basal section. Ord. L.
Showing form and zoning.

Alteration. None.

Pleochroism. Vertical sections with colour are strongly pleochroic; oblique sections feebly pleochroic, and basal sections non-pleochroic. The possibility of the absence of pleochroism should be borne in mind when examining fragments whose orientation is not known. In well-formed vertical sections, it will be observed that when the length is arranged in a N.S. direction the maximum absorption is taking place.

Pol. Colours. 2nd order colours common; but when the absorption is strong, polarisation colours are obscured. Basal sections isotropic.

Extinction. Straight.

Twinning. None.

Resemblances.—When the crystals are small, vertical sections of brown tourmaline resemble biotite or hornblende; but either of these may be distinguished from tourmaline by an application of the pleochroism test. The dark extreme of tourmaline is seen when the length is N.S. The dark extreme of biotite or hornblende is seen when the length is E.W.

Topaz. — $(AlF)_2SiO_4$. *Orthorhombic. Cleavage parallel to* 001 *(basal). Birefringence positive.*

Colour. None.

Form. Usually rounded or irregular.

Cleavage. Rarely seen.

Ref. Index. 1·62. Good relief.

Alteration. None.

Pol. Colours. 1st order.

Twinning. None.

Resemblances.—The characters of topaz are much like those of quartz, and some difficulty is experienced in making the distinction. An exhibi-

tion of cleavage settles the point at once in favour of topaz, but it is not often available; the most useful distinction is that of refractive index—a distinction which students should lose no time in endeavouring to appreciate. The minerals may also be distinguished in convergent light.

THE SILICATES OF ALUMINA

There are three important minerals coming in this group :—

Andalusite.   *Orthorhombic.*
Sillimanite.   *Orthorhombic.*
Kyanite.   *Triclinic.*

Andalusite.—$Al(AlO)SiO_4$.   *Cleavage*   110   (*Prismatic*).   *Birefringence negative.*

Colour.	Pale pink to colourless.
Form.	Usually in rounded grains, but occasionally showing rhomb-shaped or elongate sections.
Cleavage.	Rarely seen.
Ref. Index.	1·64. Good relief.
Pleochroism.	Pale pink or colourless.
Pol. Colours.	1st order greys.
Twinning.	None.

Resemblances.—The mineral resembles apatite somewhat closely, but the pale pink colour and the form, together with the absence of isotropic sections, are useful means of distinction.   Also distinguished by biaxial figure in convergent polarised light.
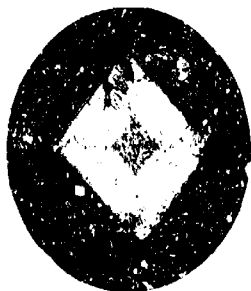
Chiastolite is a variety with characteristic inclusions.

Sillimanite.—Al_2SiO_5.   *Cleavage* 010 (*Brachypinacoid*).   *Birefringence positive.*
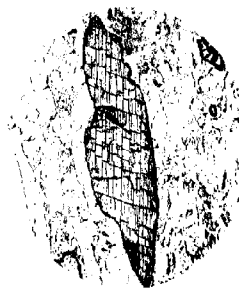
Colour.	None.
Form.	Commonly acicular, but sometimes irregular.

PLATE XI

1.—Chiastolite, basal section. Ord. L.
Showing form and inclusions.

2.—Kyanite. Ord. L. Showing cleavages
and high refractive index.

3.—Epidote. Ordinary Light. Showing
form and cleavage.

4.—Epidote. Ordinary Light. Showing
occurrence in amygdule.

Cleavage.   Rarely seen.
Ref. Index. 1·67. Good relief.
Pol. Colours. 1st and 2nd order.

Resemblances.—Distinguished from apatite by its higher polarisation colours, and by biaxial figure in convergent light.

Kyanite.—$(AlO)_2SiO_3$.   *Cleavage* 100 *(Macropinacoidal) and* 010 *(Brachypinacoidal). Birefringence negative.*

Colour.   Colourless; rarely pale blue.
Form.   Irregular.
Cleavage.   Usually well seen in one direction. Occasionally two are seen.
Ref. Index.   1·72. Good relief.
Pleochroism. Feeble—pale blue to colourless. May be absent.
Pol. Colours. 1st and 2nd order.

Resemblances. — The colour (if present), cleavage, and refractive index, are sufficient to distinguish the mineral from any other. Hauyne is sometimes blue, but the colour is almost the only point of resemblance. Glaucophane is distinguished by its lower refractive index and its peculiar colours and pleochroism.

Epidote.—$Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$.   *Monoclinic. Cleavage* 001 *(Basal). Twinned on* 100 *(Orthopinacoid). Birefringence negative.*

Colour.   Pale yellow green (pistachio green).
Form.   Usually granular or irregular. Occasionally idiomorphic, with transverse sections exhibiting resemblances to those of hornblende.
Cleavage.   In one direction, but not always seen.
Ref. Index.   1·76. Very good relief.
Pleochroism. Feeble : pale green to darker green.
Pol. Colours. 2nd and 3rd order. Very bright colours.
Twinning.   Rarely seen.

Resemblances.—Epidote is distinguished from pyroxenes and amphiboles by its colour and higher refractive index; from sphene and garnet by its bright polarisation. Tourmaline is sometimes very similar in appearance when in irregular masses, but epidote may be distinguished by its peculiar colour, superior cleavage, higher refraction, or brighter polarisation; and in convergent light by its biaxial interference figure.

Zoisite. — $Ca_2(AlOH)Al_2(SiO_4)_3$. *Orthorhombic. Cleavage* 010 *(Brachypinacoid). Birefringence positive.*

A mineral closely related to epidote in composition, but differing very widely from it microscopically.

Colour.	Usually none.
Form.	Variable.
Cleavage.	Rarely seen.
Ref. Index.	1·70.
Pol. Colours.	1st order grey or ultra-blue.

Resemblances.—Distinguished from apatite by absence of form, higher refractive index, or ultra-polarisation; also by its biaxial interference figure.
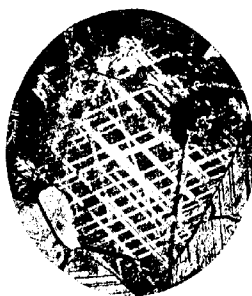
Calcite.—$CaCO_3$. *Hexagonal. Cleavage Rhombohedral. Birefringence negative.*

Colour.	None.
Form.	None.
Cleavage.	Good. In two or three directions.
Ref. Index.	1·57 approx.; but varies with the direction of section.
Alteration.	None.

PLATE XII

1.—Calcite. Ord. L. Showing cleavages and the occurrence in amygdule.

2.—Calcite. Crossed nicols. Showing lamellar twinning.
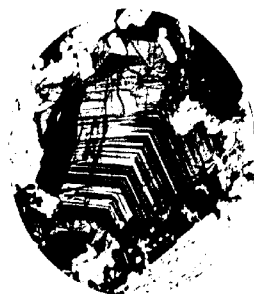

3.—Dolomite. Ordinary Light. Showing form and zoning.

4.—Zeolites. Ord. L. Showing occurrence with vermicular chlorite in amygdule.

5.—Cordierite. Ordinary Light. Showing haloes round inclusions.

6.—Cassiterite. Ordinary Light. Showing zoning.

Pleochroism.	None. But there is often a striking change of relief when the test is applied, the result of the high double refraction. *This change, when the polariser or the stage is rotated rapidly, gives the effect known as twinkling.*
Pol. Colours.	Pale pinks and greens or high order greys.
Twinning.	Lamellar.

Dolomite.—$CaCO_3MgCO_3$. *Hexagonal.*

Has many points of resemblance to calcite, but has crystals with a rhomb-shaped outline, and often well-marked colour zoning.

Zeolites.—*Hydrated silicates of aluminium with various alkalies and alkaline earths.*

The group known as Zeolites is a very large one, the different individuals differing greatly.   As a rule, they are found filling cracks or cavities.

They are colourless, and have a refractive index near to that of Canada balsam. Two of the most important are ANALCIME (cubic) and NATRO-LITE (orthorhombic); the latter occurs as acicular crystals polarising in 1st order colours.   Anal-cime may occur in cavities, possibly as a secondary mineral, but there is strong evidence in support of the idea that it (and zeolites in general) has crystal-lised as a normal igneous constituent.

Cordierite.—*Silicate of magnesium, iron, and alu-minium.   Orthorhombic.   Cleavage* 100, 010, & 001 *(macro-, brachy-, and basal pinacoids).   Birefringence negative.*

Colour.	None.
Form.	Usually allotriomorphic.
Cleavage.	Not conspicuous, but may often be seen.
Ref. Index.	1.54. Almost equal to that of Canada bal-sam.

Alteration.	Commonly alters along cracks, forming turbid, pale greenish streaks.
Pleochroism.	None, save around minute inclusions, which often produce beautiful pleochroic haloes.
Pol. Colours.	1st order.
Twinning.	Occasionally seen. Simple, lamellar, or cyclic.

Resemblances.—May be distinguished from quartz and felspars by the pleochroic haloes, which, although not necessarily conspicuous, may nearly always be found; also distinguished from quartz by its cleavages, twinning, and biaxial interference figure.

Cassiterite (Tinstone).—SnO_2. *Tetragonal. Twinned on 101 (2nd order pyramid). Birefringence positive.*

Colour.	Brown.
Form.	Usually irregular or granular.
Cleavage.	None.
Ref. Index.	2·00. Very high relief.
Zoning.	Colour zoning common and well shown.
Pleochroism.	Feeble.
Pol. Colours.	High order greys, but usually masked by the body colour.
Twinning.	Simple twins common.

Zircon.—$ZrSiO_4$. *Tetragonal. Twinned on 101 (2nd order pyramid). Birefringence positive.*

Somewhat like apatite, but distinguished by its much higher ref. index (1·95), and by its polarisation colours. These latter are high order greys, with, in a few cases, pale pinks and greens of a high order. The distinction between the two minerals is not an easy one, as the greys of a high order may be very similar to those of the first order shown by apatite, but the distinction may be effected by the form of the cross sections and the sign of double refraction.

THE OPAQUE MINERALS

Magnetite.—$FeOFe_2O_3$. *Cubic.*

Ilmenite.—$FeTiO_3$. *Hexagonal.*

Pyrites.—FeS_2. *Cubic.*

As these minerals are opaque, it will be seen that the only available method of examination is that by reflected light.

Pyrites, thus examined is seen to be brass yellow.

Magnetite and ilmenite are black when fresh, but when decomposed, the one can be distinguished from the other. The alteration product of magnetite is brown or yellow, that of titanoferrite is white, and its development has often taken place so as to form triangular geometrical patterns.

THE STUDY OF ROCKS

IGNEOUS ROCKS.—Evidence regarding igneous activity is presented to man during every volcanic eruption; and though the witnesses do not in all cases survive to record their observations, and the state of mind of others is not such as to permit them to note the phenomena in a detached frame of mind, sufficient first-hand evidence is available to satisfy us that there is a mass of reliable information regarding the phenomena displayed. This particularly applies to the milder activity that in many cases succeeds the more violent manifestations. Moreover, the lavas and fragmental materials ejected during the period of major activity are available for subsequent examination.

Cessation of surface activity, however, does not imply that all the igneous matter has been extruded. It is quite certain that much liquid material (magma) fails to reach the surface and is cooled somewhere within the earth's crust. This intruded material cannot, for obvious reasons, be observed at the time of injection, but many examples of early origin are now exposed at the surface because of subsequent denudation of a thickness of overlying, older rocks, measured perhaps in miles. Any conclusions regarding the

history of such intrusive bodies must of necessity
be largely in the nature of inference, and are
bound to be coloured to some extent by the pre-
dilections of the observer.

It is not surprising, therefore, that many
theories of igneous action are extant. Dogmatic
statements are available for assimilation by those
who are inclined to accept them, but it would seem
advisable at the present time to avoid hasty con-
clusions, while becoming familiar with the several
views advanced by different workers. Any opinion
expressed by a worker of adequate experience is
worthy of respectful consideration, but belief in it
is not obligatory.

It may be objected that, since there is so little
certainty regarding modes of origin, it would be
better to ignore the literature and to rely entirely
on personal observation. Such a procedure may
perhaps be the best possible for a genius, but to
the ordinary man the views of others are essential ;
he should see to it that he has an open mind while
taking steps to ensure that it is not vacant.

Some theories that must be considered, postu-
late basalt as a primary magma. The rock is a
mixture of augite, olivine and plagioclase (about
labradorite), together with a few other minerals in
smaller quantities, and perhaps a certain amount
of uncrystallised material as glass. Basaltic
lavas have been erupted in great quantities at
different periods and in many areas, and they
must have come from a horizon within the
earth's crust or beneath it. On account of

the remarkable similarity between these basalts of different ages and different areas, many geologists believe that these flows were fed from a continuous layer underlying all continents and oceans; and that the continents, perhaps twenty miles thick, are floating in this substratum much as an iceberg floats in water.

If this belief be well-founded, the tensions that develop from time to time in the continents produce fissures which gave a passage-way enabling the liquid basalt to emerge at the surface by way of one or a series of these, more or less parallel. These effusions constitute fissure eruptions, but they differ in no essential from those emitted at volcanoes, since the latter, often with linear arrangement, merely result in consequence of local plugging of a fissure. By such means, what was part of the liquid substratum appears at the surface of the earth, and its very constant characters suggest that it reaches daylight in an unchanged condition as far as composition is concerned. If such a picture represents the facts, we may perhaps be permitted to suppose that when the ascent through the crust ceases, there is left, frozen in this, a series of great, wall-like masses of basaltic rock, extending from substratum to surface as dykes.

In other cases, however, the time factor enters; portions of the substratum ascend slowly within the crust and lose heat continuously to the adjacent country rocks. In such circumstances, it is possible for certain chemical compounds to

separate from the intrusive liquid, the magma, in the form of crystals. Among the earliest of these are olivine and augite; these are followed by lime-felspars, hornblende, and later by biotite and alkali felspars, together with quartz.

It will be obvious that if a mineral like olivine crystallises from such a magma, the residual liquid will have become poorer in iron and magnesium; indeed, in the very improbable event of such crystallisation proceeding to the limit, both these elements would then exist in the crystals but not in the liquid. Crystallisation of one mineral, then, means separation of certain constituents from the liquid; it means also that the residual magma becomes relatively richer in those constituent elements not required by the crystals; the liquid becomes progressively richer or progressively poorer, according to which of these we have in mind.

Such facts have long been appreciated, and it is customary for petrologists to speak of increasing acidity of the residuum, on the assumption that a silica-rich liquid represents the final phase. Dr. Bowen, however, considers that the essential increase is not in silica, but in alkalies; that in the later stages the liquid becomes poorer in silica. He pictures the earlier minerals crystallising, and because they are heavier than the liquid, sinking; this sinking proceeding, unless prevented by increasing viscosity, until they have reached the bottom of the magma chamber, or until they are trapped in a mesh-work of other crystals.

In such circumstances, if the liquid life of the reservoir is sufficiently prolonged, we should expect the magma chamber to be stratified according to the order of crystallisation of the constituent minerals; we should also expect the last-formed crystals to occupy the uppermost part of the magma chamber. Moreover, on Bowen's hypothesis, we should expect the minerals there formed to be rich, not in silica, but in alkalies.

All this takes place well below the surface of the earth, hence the resulting rocks are known as plutonic; it takes place under conditions of slow cooling, and therefore crystalline rocks are formed; hence the name of holocrystalline applied to them. Clearly, any exposure of such rocks at the surface means that the pre-existing, overlying strata have later been removed by denudation. In such a magma chamber, where the liquid life has been long enough to enable differentiation to proceed to the limit, the plutonic rocks should be arranged (on Bowen's hypothesis) in descending order, graduating one into the other, as follows :—

Rocks.	*Essential Minerals.*
Nepheline Syenite	Nepheline, alkali felspars.
Syenite	Alkali felspars.
Granite	Alkali felspars, quartz.
Diorite	Lime-soda felspars.
Gabbro	Lime felspars, olivine, augite.
Peridotite	Olivine, augite.

The particular variety of plutonic rock exposed at the surface to-day will depend on the extent to which denudation has proceeded. Thus, Bowen explains the difference between the plutonic rocks

of the Rocky Mountain region and those of
Montana by suggesting that those of the former
area (granites) represent deeper denudation than
those of the latter, which are definitely richer in
alkalies.

It must not be supposed, however, that this com-
plete layering is always attained. The process is
only allowed to proceed to the limit in the case of
those reservoirs having a sufficiently long liquid
life. Freezing may take place at any stage, and
therefore the uppermost plutonic rock may be
syenite, granite, diorite, or even gabbro if freez-
ing supervenes at an early stage.

So far, we have adopted Bowen's theory of
crystal differentiation, taking it as demonstrated
that the work of gravity was performed after the
beginning of crystallisation. It is possible, how-
ever, that differentiation was effected at an earlier
stage. Some liquids form homogeneous mixtures
at high temperatures, but later cooling results in
the separation of the two liquids, the heavier be-
low and the lighter above. If such a procedure
operates in the case of magmas, gravity separation
does not depend on the sinking of crystals; more-
over, the contact of two types of plutonic rock is
likely to be sharper than under the conditions
postulated by Bowen. Perhaps each is an im-
portant factor. In any case, the results may be
much the same as far as the broad outlines are
concerned.

Professor Daly, who sponsors this theory of
liquid immiscibility, points out an interesting con-

sequence of progressive differentiation.   He calls
attention to small masses of diorite occurring in
satellitic fashion around large granitic areas, and
explains them by supposing that, at one stage of
differentiation in the chamber, some of the magma
was ejected from the upper part of it into the
adjacent rocks.   There it solidified rapidly (rela-
tively) because of loss of heat to the cold rocks in
contact;   no further differentiation was there
possible, and a diorite was formed.   But in the
parent magma chamber, the liquid life being
longer, differentiation proceeded to a later stage
and granite was produced near the summit.

Another interesting phenomenon is explained
by the same worker.   In the case of some plutonic
masses, the marginal portions are more basic (*i.e.*,
poorer in silica) than the rest of the rock.   Vari-
ous suggestions have been advanced to account for
this, but Daly's explanation may be accepted as
the most satisfactory.   A magma in an early stage
of differentiation occupies a part of the earth's
crust, freezing on the walls may be expected, and
there is thus formed a fringe in which the changes
proper to the liquid state are no longer possible.
In the central part of the chamber, however, loss
of heat is much less rapid, gravity adjustments
may be effected and therefore, near the roof, a late
phase will immediately underlie, and will be sur-
rounded by, an earlier one.   There are a few cases
in which the margin is relatively acid (*i.e.*, richer
in silica) but in those cases the main mass is a
nepheline syenite or allied rock, and this sort of

thing is to be expected if, as Bowen contends, alkali-rich rocks succeed the granitic stage.

The occurrence of dioritic satellites gives rise to some interesting speculations as to the sequence of minor intrusions. It is not to be expected that a great magma chamber will be free from disturbance by earth movements during the whole period of crystallisation, and any squeeze is liable to result in the transfer of some of the magma from the main chamber into the country rock. If we imagine the reservoir to be compressed at intervals before completion of crystallisation, intrusions from near the top of it will be progressively richer in alkalies, and possibly silica. Consequently, if two such intrusions are found associated, we should expect the more acid one to be later than, and possibly to cut, the more basic rock. The question is, however, a complicated one, because the area under consideration may have received contributions from two adjacent batholithic chambers. Moreover, in a satellitic chamber the liquid life may be prolonged to some extent, differentiation of its partial magma may take place, and ejection of its liquid residuum may follow.

The reality of gravity differentiation of some kind is demonstrated by examination of certain of the thicker sills. In the case of the thinner examples, cooling must have been sufficiently rapid to preclude the possibility of gravity adjustments, but where the bulk of the magma was great enough, cooling was slower, and in the examples where both floor and roof are exposed to view,

basic rock is found to graduate up into one that is definitely acid.

Assuming, as has so far been done, that basaltic magma is the parent of all the other igneous rocks, the probability of the contamination of the magma has to be considered. It is quite certain that in some cases, the igneous rock occupies a space which came into existence because of the displacement of the pre-existing rocks, the magma having forced these aside or having occupied a chamber opened up by earth movements. A laccolite, for example, with a plane lower surface and a convex upper one, may very well result from emplacement of a magma which lifted up the superincumbent rocks. But by definition, a laccolite has a floor of older rocks, and this floor is not always visible. Such a great granite mass as that of Dartmoor, for instance, may be a laccolite, but the floor is nowhere exposed, and the mass may extend downward indefinitely; it may, in fact, be a batholith. Now if this be the case, it is difficult to see how the magma could have come to occupy its present position by mere displacement. Hence, Daly and others claim that the rocks that formerly existed there have been incorporated in the magma; they have been assimilated, and therefore the magma is no longer purely igneous in character. By this school it is contended that such assimilation of silica-rich material, and subsequent gravity adjustments, are necessary to produce the granitic differentiate.

To explain the existence of alkali-rich rocks like

nepheline syenites, the assimilationists go a step further. They are impressed by the very common association of such intrusive rocks with limestone; they consider that calcareous fragments have been detached by the granitic magma and that reactions involving the using up of silica have taken place; that the magma has, in fact, been desilicated, with the result that silica-poor minerals like felspathoids have come into being. On these questions of the origin of granite and nepheline syenite, then, the two schools of thought are definitely opposed; one of them derives all varieties by the sinking of crystals, the other demands the assimilation of great masses of country rock.

That portions of the country rocks are caught up by the magma admits of no doubt; these " xenoliths " are to be observed in numerous granitic masses. They, in many cases, are easily recognisable as such, being enclosed in the igneous rock without having suffered any appreciable change.   In other examples, interchanges between magma and xenolith have taken place to such an extent that the latter is barely recognisable as such.   That being so, the question at once arises as to how much of this incorporation, leaving no trace, has been effected.   To that, of course, no satisfactory answer is available. Dr. Harker was of the opinion that the magma was never hot enough to do the work on a large scale, while, on the other hand, Daly demanded whole-sale incorporation.   Bowen answered Harker's objection by showing that the importance of

superheat had been much exaggerated, and that
this process of incorporation may take place to a
considerable extent even though the temperature
may never have been much higher than that at
which crystallisation commenced.   There is no
possible doubt, then, that many of the intrusive
rocks now available for our examination have been
to a greater or less extent modified as a result of
the incorporation of portions of the pre-existing,
country rocks, and this modification may or may
not be recognisable when the rock is examined
under the microscope or by means of chemical
analysis.

The parallel structures exhibited by certain un-
doubted intrusive igneous rocks may be explained
as being due to movement at a stage when xeno-
lithic material had been incompletely digested.
Movement of the magma at this stage may justi-
fiably be invoked and the drawing out of the
softened foreign material into streaks may be
taken as a natural consequence.   Another possible
explanation of such fluxion structures is to be
found in the theory of liquid immiscibility; if we
admit the possibility of the existence of silicate
magmas that refuse to mix, then the development
of this streaky character of the resulting composite
rock follows as a natural consequence.

A certain degree of assimilation of country rock
by magma may be taken as established fact, but
this migration of xenolithic matter to intrusion is
not the only kind of transfer.   It is quite certain
that at different stages of cooling, material is
exuded by the magma into the country rocks.   The

rock known as adinole, rich in silica and soda
(making albite), occurs where a slaty rock is in
contact with some basic intrusion, and there is no
doubt that this " albitisation " is the result of such
transfusion. Similarly, lime and iron silicates
occur in limestones adjacent to some granitic in-
trusions. These "skarns" are undoubtedly due
to a process analogous to that of albitisation. In
addition, the occurrence of many ore deposits,
such as those of copper, tin, and tungsten in the
neighbourhood of igneous contacts, bears witness
to the fact that solutions of various kinds have
passed the junction and have laid down their bur-
den in the country rocks, either in fissures or
actually replacing pre-existing minerals by a pro-
cess known as metasomasis. The reason for the
precipitation in fissures is not always clear, but
diminishing temperature away from the intrusion
is one probable cause, decrease of pressure in the
case of ascending solutions is another. Condi-
tions of chemical stability enter where solutions of
magmatic origin encounter those descending from
the surface, and also in the case of those of meta-
somatic origin. Water has played an essential
part in this process of transfusion, and it seems
necessary to accept this as an integral part of the
magma, although it is just possible that it may
have been acquired by incorporation of water-bear-
ing country rocks at an earlier stage of the
magmatic history.

There is some difficulty in accepting liquid
water as a medium of transfer at great depth, but
gases may penetrate where liquids can not, and

the water is probably in the gaseous condition.
Other gases also operate, and carry with them
magmatic constituents responsible for the manu-
facture of many other deposits, particularly those
of cassiterite and wolfram; the process is that
known as pneumatolysis. Exudations of this kind
seem to have taken place at high temperatures and
probably precede those in which liquid water is
concerned, but no doubt their periods of emission
overlap to some extent.

It should be borne in mind that the central parts
of a large intrusion remain liquid at a period when
the marginal portions have become chilled, and
therefore these solutions, in liquid or gas, travel-
ling outward from this core, are compelled to
traverse rock of igneous origin before reaching the
country rocks, therefore precipitation may occur in
the igneous rock already solidified, at the contact,
or beyond. The particular point at which deposi-
tion takes place depends on a variety of causes,
but naturally, the high temperature minerals will
be laid down nearer the source of origin, those
able to remain in solution at lower temperatures
may be carried to some considerable distance before
precipitation takes place; hence their magmatic
origin is not always obvious.

The transfer of igneous material means, of
course, that the volatile constituents can no longer
be contained in their entirety by the magma. This
result must follow as a consequence of crystallisa-
tion, because the amount of residual magma is
continually decreasing, and there must come a

time when the volatiles, which have not been ab-
stracted to form crystals, become too voluminous
for their more and more contracted quarters. It
seems legitimate to expect, then, that metasomasis
and pneumatolysis will commence soon after the
beginning of crystallisation, and will continue as
long as any liquid remains. Full data are want-
ing, but certainly much pneumatolytic activity
takes place during and after the granitic stage.
Tourmaline and topaz, rich in boron and fluorine
respectively, are undoubtedly a consequence, in
some instances, of this gaseous transfer; and they
are frequently found replacing minerals of granite
like orthoclase and biotite; likewise, beautiful
pseudomorphs of cassiterite after felspar are found
in these rocks.

It may be taken as demonstrated, then, that
neither intrusion nor country rock retains its
original bulk composition; it is permissible for
anyone, however, to form his own opinion as to
the extent to which such transfer has taken place
in particular cases.

So far, we have considered the conditions under
which intrusive igneous rocks may have been
formed, the top of the basaltic wedge or magmatic
chamber having failed to reach the earth's surface.
But there is no fixed limit for the summit of such
an intrusive body, and there must have been many
cases in which communication with the light of
day was effected, and the particular differentiation
product developed at the time at that summit was
ejected at the surface and formed an extrusive

igneous rock.   Assuming the conditions to be
such as have been outlined, the composition of
this volcanic rock will clearly depend on the par-
ticular stage of evolution reached at that time in
the chamber below.   We may thus expect to find
volcanic rocks comparable in composition with the
plutonic rocks, the mineral content of which has
been briefly indicated.   There are, however, some
conditions peculiar to igneous rocks formed above
ground.   In the first place, cooling at the surface
is more rapid than it is underground, not because
air is a better conductor than rock, but because
convection ensures constant removal of heat from
the cooling surface.   Slow cooling facilitates cry-
stallisation, therefore volcanic rocks tend to be
non-crystalline or glassy.   In the second place,
escape of volatile constituents from the surface of
a lava is much easier than it is in the case of an
intrusive magma.   Now it is safe to say that the
presence of these volatiles facilitates the formation
of crystals, and that their absence renders crystal-
lisation difficult or impossible.   For two reasons,
therefore, extrusive igneous rocks should contrast
with their intrusive counterparts by being glassy
instead of crystalline. On the whole, this expecta-
tion is justified, but there are, of course, some
exceptional cases where crystals have grown in the
surface flows after extrusion, and some where in-
trusive rocks are glassy.   Moreover, the volcanic
rock may contain crystals of subterranean origin;
this must be the case because extrusion is an inci-
dent which takes place during the period of cry-

stallisation of the feeding magma, and these crystals must in certain cases be carried to the surface and will be found embedded in the rock, glassy or otherwise, formed by solidification at the surface.

The lava after extrusion will, of course, flow down any slope on which it may rest, until further movement is rendered impossible by increasing viscosity. During the movement, any contained elongated bodies, crystalline or otherwise, will be drawn out in the direction of flow, and thus a fairly characteristic texture is developed in the rock; it must be remembered, however, that flow before extrusion may, exceptionally, produce somewhat similar results in intrusive rocks. Another important peculiarity of extrusive rocks follows as a consequence of their mode of origin. Escaping gases cause bubbles to form at the surface of the lava; these develop in great numbers, and the gases burst through to the open air. A vesicular or scoriaceous texture is the result. Most of the vesicles are ellipsoidal in shape, the longer axes indicating the direction of flow. These glassy and vesicular characters may thus be expected to develop at the surface of the lava stream, the central part of the flow may be glassy or crystalline. Any part of the flow, however, may contain crystals of subterranean (intratelluric) origin.

In some cases (*e.g.*, Antrim and Mull) such flows rest on plant remains which enable the date of the extrusion to be fixed with a fair amount of accuracy.

If the eruption was not effusive, but explosive,
fragments of lava and other rocks were hurled vio-
lently up into the air, to come down later and form
a deposit which, like an ordinary sediment, may
enclose examples of the life of the period and thus
enable the age to be determined by the fossil test.
Such rocks are known as volcanic ash, tuff, or
agglomerate.   They will, of course, present evi-
dence of clastic origin when examined with or
without the aid of the microscope.

In considering the extrusive rocks, it has to be
remembered that the glassy state is unstable.
Even old glasses made by man have in some in-
stances made attempts at crystallisation, and those
of igneous origin, particularly the older ones, fre-
quently exhibit similar phenomena.   Crystals
formed under such conditions tend to be acicular
and to be grouped radially about a point ; they are
most common in acid rocks and the aggregations
are known as spherulites.   The fact that flow
bands frequently traverse them shows in those
cases that the crystallisation is of later date.
Also found in glassy rocks are curved cracks
known by the name " perlitic." Where crystal-
lisation after solidification (devitrification) has
been considerable, it is sometimes difficult to
recognise the fact that the rock was originally
glassy ; in such cases the existence of perlitic
structure may be distinctly useful in the attempt to
work out the history of the rock.

As in the case of minor intrusions, elucidation
of the history of a volcanic area is attended by

considerable difficulty. Where one flow rests upon another, it is clear that the upper one is the newer, but it is not always possible to get conclusive evidence of superposition. Assuming the truth of Bowen's sequence, that richer in alkalies should be the newer. But even making this assumption, it is not certain that all the flows of one area came from the same reservoir, and therefore this particular test is inapplicable. In any such area the sequence must be worked out by painstaking collection of evidence on the ground.

The orthodox classification of plutonic rocks according to composition may be indicated as follows:—

GRANITE	Acid	
		66% Silica
SYENITE DIORITE }	Intermediate	
		52% Silica
GABBRO	Basic	

Thus, granite is that plutonic rock which is specially rich in silica, and therefore contains felspars rich in the orthoclase or albite molecule, together with quartz; these are usually accompanied by one or both micas, and, perhaps, apatite and sphene. Gabbro is poor in silica, and consists of a felspar rich in the anorthite molecule, together with a pyroxene and, usually, olivine; apatite and iron ore may be present. Of the two intermediate classes, syenite is rich in alkalies, while diorite is poor in them. In both cases, certain ferro-magnesian minerals like augite and/or hornblende are included; while biotite, apatite and sphene may

be there, the latter mineral particularly in syenites.
The chief minerals in these intermediate rocks,
however, are the felspars; syenite has orthoclase,
microcline, or a soda-lime felspar close to albite in
composition; the felspar of diorite ranges about
andesine, although zoned examples are common,
and of course, each zone has its own particular
composition. But both syenite and diorite may
contain a little quartz, thus indicating an approxi-
mation to the granitic end of the series. Now if
the tabular statement above represents the facts,
a quartz syenite is a reasonable possibility but a
quartz diorite is absurd. Although there is much
difference of opinion regarding rock nomencla-
ture, there are fairly common rocks which all
petrologists are agreed to call quartz diorites. It
therefore seems better to adopt a scheme such as
that represented by diagram A. This method of
grouping allows for the existence of types transi-
tional between syenite and gabbro, gabbro and
diorite, syenite and granite, and granite and
diorite, all of which undoubtedly exist. A similar
grouping may be adopted for those igneous rocks,
usually found as dykes and sills (minor intrusions)
which, on the whole, have a finer texture than the
corresponding plutonics, or contain their minerals
embedded in a glassy matrix. They are usually
referred to as hypabyssal (diagram B).

The corresponding volcanic rocks may be
grouped in a similar way. Theoretically, these
are the glassy rocks, and they do usually contain
a certain amount of uncrystallised material; this is,
however, usually very scarce in the case of basalts

Rich in Alkalies	Poor in Silica
SYENITE	**GABBRO**
GRANITE	**DIORITE**
Rich in Silica	Poor in Alkalies

A

Rich in Alkalies	Poor in Silica
FELSITE	**DOLERITE**
QUARTZ FELSITE	**PORPHYRITE**
Rich in Silica	Poor in Alkalies

B

Rich in Alkalies	Poor in Silica
TRACHYTE	**BASALT**
RHYOLITE	**ANDESITE**
Rich in Silica	Poor in Alkalies

C

(see diagram C). If each of these three diagrams
is drawn on a card and then superposed thus:

C
B
A

so that granite, quartz felsite, and rhyolite form
a vertical series, we get a scheme of classification,
based on composition and texture, which is fairly
satisfactory. This scheme can be shown in a more
striking manner by using, for each of these twelve
subdivisions, a small box; the whole then is obvi-
ously of three dimensions.

There are, of course, many names given to dif-
ferent varieties of igneous rocks—names not men-
tioned in this brief summary—but it is believed
that the scheme here suggested is the best at
present available, and with this in mind, the
student may proceed to the perusal of larger works
and will find it a useful foundation. No claim to
finality is implied; a perfect scheme of classifica-
tion will be based on complete knowledge of
igneous processes. As it is not even certain that
basaltic magma is in any sense parental, those who
reject this hypothesis will certainly regard some
of the preceding pages as unsatisfactory. Only
one alternative theory will here be examined,
though certain other suggestions will be made
near the end of this book.

The crystallisation of any igneous magma takes
place with falling temperature, and during this
temperature interval, the several minerals separate
from the magma in a more or less definite order.

For instance, olivine crystallises at a higher temperature than does alkali felspar. It might be expected that a high temperature mineral would suffer changes in its constitution such that it would always be in equilibrium with the residual magma, and, in fact, such adjustments do take place to a limited extent. Thus, olivine→pyroxene→amphibole→biotite, represents a series of changes which certainly have taken place during the crystallisation history of some igneous rocks. But perfect equilibrium with the final magma is never attained, and the rock is thus made up of minerals, some of which are not strictly proper to the lower, later temperatures.

Moreover, certain mixtures remain liquid at temperatures lower than the melting point of the pure substances. Considering for the moment, elements instead of minerals, one may be almost infusible, while another melts at a moderately low temperature; but a suitable mixture of the two metals will fuse at a temperature lower even than that of the latter. There are certain disturbing factors, but broadly, the generalisation holds good. Similar considerations apply to the minerals of igneous rocks—quartz and orthoclase for example. Regarding crystallisation as the reverse of fusion, it follows that there is no fixed temperature of crystallisation for any mineral; it is governed largely by the other constituents building up the magma. Now suppose that conditions are such that an igneous rock like granite is re-heated. The melting will not be exactly the reverse of the order followed during

the crystallisation, because certain of the volatile constituents have undoubtedly departed permanently from that particular area; the bulk composition of the granite is not exactly the same as that of the magma from which it was formed.   It is not to be supposed, however, that the sequence of melting will differ in any very marked degree from that which would be an exact reversal of crystallisation.   At a suitable temperature, fusion will commence, and will continue in the order governed by the properties of the individual minerals and the proportions in which they are associated.   Part of the rock will be fused, and if the heat supply is adequate, the whole of the rock will suffer a similar fate.   Thus, part of the rock or the whole of it will become mobilised.   But similar considerations apply to rocks other than granites; any rock in such circumstances is liable to suffer from this process of anatexis, but the components that fuse most readily are those elements that can combine to make granite.   There is thus a selective fusion, the " non-granitic " constituents will often be left unfused, while the mobilised " granite " will be free to respond to earth pressures, to depart from regions of high to those of low pressure, and thus, on the whole, to rise towards the surface of the earth.   If we take the view that the theatre of this fusion is too deep for much of it to have been exposed at the surface as a result of subsequent denudation, we shall have a satisfactory explanation of the fact that, of the exposed plutonic rocks, granite is by far the most common.   This suggestion is that developed by

Eskola, and he has thus indicated a method by which a granitic magma may come into being quite independent of the existence of a basaltic parent. The mineral composition of a rock produced as a result of crystallisation from a magma originating by anatexis will, of course, depend on the degree of partial fusion, and thus, rocks more basic than granite may be produced in this way; contamination with basic material after the initial fusion is another possible explanation of a diorite, even though the fusion resulted in the melting of granitic minerals only. The heat necessary for anatexis is considered to be available because of subsidence in a particular area carrying down a part of the earth's crust into the depths, where temperatures are undoubtedly high.

SEDIMENTARY ROCKS. — The operations of denudation and deposition are so completely bound up with the appearances presented by these rocks that it is quite hopeless to attempt their study without a good knowledge of the processes. That knowledge will be assumed, and only the lines along which the examination of the rocks should proceed will be indicated.

As in the case of igneous rocks, hand-specimens should always be examined if available.

Arenaceous Rocks (pebbly and sandy).—In the attempt to elucidate the history of a conglomerate, thin sections of the pebbles may often be examined with profit; because clearly such fragments are portions of rocks which formed the land surface at the time of accumulation of this particular deposit; and the investigator, if he can, by

lithological comparison, determine with certainty
the rock-mass from which the pebble was derived,
is able to obtain valuable information regarding
the time at which deposition was effected.   Thus,
fragments of Shap granite are found in a con-
glomerate at the base of the Carboniferous Lime-
stone.   It follows that the intrusive rock is
pre-Carboniferous in age; it had even been " un-
roofed " before deposition of that limestone
commenced.   Conversely, if the age of the parent-
rock is known, information regarding the age of
the deposit resulting from its erosion is available;
and as the Shap granite is known to be of post-
Silurian date, it follows that the conglomerate
containing fragments derived from it is later still.

In recent years, much work has been done on
sandy rocks, the same principles being applied;
the constituent minerals are determined and
attempts are made to visualise the nature of the
rocks forming the old land surface from which the
materials were denuded.   First, sections of the
sandstone should be made in the ordinary way.
The minerals existing as grains should be identi-
fied, and the nature of the cementing material
determined.   The degree of rounding and angu-
larity of the grains should be noted.   As a result
of the mode of formation of such rocks, there has
usually been such a selection of mineral fragments
that the bulk of these derived constituents is made
up of minerals which are not decomposed by tritu-
ration in atmospheric waters; and as quartz is by
far the most common of these, that mineral is the
most conspicuous constituent.   In those cases,

however, where the accumulation of the detritus to form the deposit was not accompanied by much water action, less stable minerals had a chance of preserving their identity; and felspar grains are fairly abundant. Many such sections may be made and examined without the discovery of mineral grains other than those of quartz and felspar, but the amount of a rock constituting a thin section is very small, and any mineral which was sufficiently stable under the conditions of the time might reasonably be expected to occur accompanying the quartz in the deposit. One object of the recent work is to discover the nature and amount of these less common minerals occurring as constituents of the sandstones.

The rock should be crushed and graded by placing the powder in the uppermost of a series of sieves, fitting one above the other, that with the smallest perforations being at the bottom, the sieves becoming coarser and coarser with ascent in the series. A little shaking will cause the fragments to separate into grades. A sample from each grade should be mounted in clove oil and examined under the microscope; it will then be clear which particular grade is most suitable for purposes of investigation.

The narrow end of an ordinary glass funnel should be fitted into a short rubber tube which should be closed by means of a spring clip. This funnel, supported in a suitable stand and nearly filled with bromoform (Sp. Gr. about 2·89) supplies the means of separating the minerals of the selected grade into two fractions, lighter and

heavier. The whole of this grade is placed in the bromoform, stirred, and allowed to stand for a few minutes. Then the lower half of the bromoform is run into a basin, this being accomplished by opening the clip. The heavy liquid in this basin may then be decanted into the stock bottle via a filter placed in a funnel. The heavy mineral grains left behind may then be washed in benzene; they will soon dry and can be mounted in clove oil or Canada balsam for examination. The lighter minerals are almost sure to be present in any thin section of the rock; it is these heavy minerals that are less common and therefore they should be collected and examined with some care. If necessary, magnetic or other methods may be used to split this heavy residue into smaller fractions.

The student who has become familiar with the appearance of these minerals as seen in thin sections will find some difficulties in the early stages for several reasons. As a result of crushing prior to grading some of the crystals will have been broken and therefore form may cease to be of any assistance even where the crystals were idiomorphic; the crushing also means that cleavable minerals will have split and will rest on the slide on a cleavage plane and therefore such planes will not be indicated by the parallel cracks previously found so useful in identification. The chief difficulty, however, is in regard to thickness. The grains will almost certainly have a greater diameter than the thickness of an ordinary thin section; moreover, however perfect the grading may have

been, the different grains will vary in size. Therefore there is no definite standard of polarisation colour for a particular mineral, and some practice is required before the difficulty is overcome.

The following minerals are those most commonly found in these heavy residues :—

Anatase.—A tetragonal mineral. Colour blue or yellow. Often tabular owing to good development of the basal pinacoid, but sometimes the pyramid is dominant. Refractive index very high, about 2·49. Between crossed nicols platy forms are isotropic; in convergent light shows a positive uniaxial figure.

Apatite.—Colourless. Occasionally as irregular grains, but most commonly as elongated crystals with well-defined prism edges. Refractive index about 1·60 and therefore has a fairly good relief. Usually clear and transparent. Birefringence, 0·004, is very low, and therefore always polarises in first order grey. Has straight extinction. With a slow wedge gives compensation when that is parallel to the direction of elongation.

Epidote.—Pale yellow green. Has a fairly good cleavage and fragments frequently rest on this. Refractive index about 1·73 and therefore relief is good. Pleochroism feeble. One of the two optic axes is approximately at right angles to the cleavage and therefore in convergent light a single eye is seen near the centre of the field; it is traversed by a single, almost straight, black band.

Garnet.—Usually pink or pale brown. Grains quite irregular in shape Refractive index about 1·80 and therefore relief is good. No pleochroism. Isotropic.

Hornblende. — Colour green or brown. Fragments usually rest on a prismatic cleavage. Refractive index about 1·65 and therefore with good relief. Pleochroic; vibration-direction giving maximum absorption slightly inclined to length of fragment. Extinction angle about 16°. In convergent light one of the optic axes emerges near the margin of the field.

Kyanite.—Generally colourless, but may be blue. Has three cleavages approximately at right angles; the fragment is usually elongated and probably rests on the best

of the three cleavages. Clear and transparent. Refractive index about 1·72; good relief. Polarisation colours usually first order. Extinction about 30°. It happens that the acute bisectrix is approximately at right angles to the best cleavage and therefore the fragment shows a complete biaxial figure with negative birefringence.

Monazite. — A monoclinic mineral. Colour generally greenish yellow with brownish patches. Usually as rounded grains bounded above and below by cleavage. Refractive index high, about 1·80. Not pleochroic. Polarisation colours high. In convergent light shows a positive biaxial figure with a small optic axial angle.

Muscovite.—Colourless. Fragments rest on the perfect cleavage. Refractive index about 1·59; fairly good relief. Clear and transparent. Between crossed nicols difficulty is encountered because the polarisation colours (first order) are much lower than those usually shown in thin section. The acute bisectrix is approximately at right angles to the cleavage and therefore the fragment shows a complete biaxial figure. Birefringence negative.

Rutile.—A tetragonal mineral. Colour either yellow or a very dark brown, almost opaque (with the condenser inserted the mineral shows a rich brown of medium shade). May be as rounded grains or as elongated crystals. Refractive index very high, about 2·62, and therefore relief is conspicuous. Pleochroism rather weak, maximum absorption with the elongation E.W., i.e., for longitudinal vibrations. Extinction straight.

Staurolite.—An orthorhombic mineral. Colour brown No cleavage and therefore the fragments are quite irregular in shape. Refractive index about 1·74; good relief. Usually clear and transparent, but may be cloudy as a result of abundant small inclusions. Pleochroism feeble. A biaxial figure with a positive sign is sometimes, but not often, seen.

Topaz.—Colourless. May be rounded or may rest on the basal cleavage. Refractive index about 1·62; relief good. Clear and transparent. Cleavage flakes always show low polarisation colours. In convergent light a positive biaxial figure occupies the centre of the field.

Tourmaline.—Colour variable, but commonly brown. May be as elongated crystals resting on a prism face, may be

rounded. May rest on a basal cleavage. In certain cases, e.g., when colour is strong and the crystal axis lies parallel to the glass slip, pleochroism is intense, maximum absorption taking place for transverse vibrations. A fragment resting on the basal cleavage will not show pleochroism. Between crossed nicols, prisms extinguish in the straight position. Basal sections are isotropic and give in convergent light a uniaxial negative figure.

Zircon.—A tetragonal mineral. Colourless. Usually as elongated crystals with well-defined terminations; may be as rounded grains. Refractive index high, about 1·93; relief good. Usually clear and transparent. Between crossed nicols shows high polarisation and straight extinction.

(Note.—In all cases when getting the interference figure with mineral grains, use the third method indicated on p. 52; remove both Bertrand lens and the eyepiece.)

Magnetite and **Ilmenite,** both opaque, black, and metallic, are common. When fresh, are difficult to distinguish, but magnetite is liable to change to red iron oxide, while ilmenite may acquire a whitish colour as a result of change to leucoxene.

In the above descriptions it is assumed that the mineral grains are mounted in Canada balsam or clove oil, each of which has a refractive index about 1·54. Some idea as to the refractive index of the mineral, just as in the case of thin sections, may be obtained by inspection of the relief exhibited by it. The Becke method may be used to give additional information in this connection, but the shape of the grains is not as a rule suitable for this purpose, what is known as the shadow method gives more satisfactory results. To apply this test, keeping the eye fixed on a particular fragment, slide some opaque object immediately underneath the stage. The field will, of course, be partially darkened, but the observer should con-

centrate his attention on the edge of the grain.   A black shadow will appear *on* one side of this, the side near to or remote from that from which the opaque object is introduced.   If the shadow appears on the " near " side, the refractive index of the mineral is higher than that of the liquid; if it appears on the " off " side, it is less.

The two cases figured are drawn on the assumption that the opaque object (a finger is suitable) comes in from the right.

Mineral > liquid.   Mineral < liquid.

A combination of the inspection and the shadow methods gives the observer some idea as to the refractive index of the mineral under investigation, and the mineral should then be mounted in a liquid having a value something near that estimated for the grain.   The following liquids will be found useful :—

Chloroform	...	...	...	...	1·45
Olive oil	...	...	...	...	1·47
Castor oil	...	...	...	...	1·48
Xylol	...	...	...	...	1·49
Oil of cedar wood		...	...	...	1·51
Monochlor benzol		...	...	...	1·53
Oil of Cloves	...	...	...	...	1·54
Brom-toluene	...	...	...	...	1·55
Dimethylaniline		...	...	...	1·56
Orthotoluidine	...	...	...	...	1·57
Cinnamon oil	...	...	...	...	1·59
Cassia oil	...	...	...	...	1·60
Iodobenzene	...	...	...	...	1·62
Monobromnaphthalene			...	...	1·66
Methylene Iodide		...	...	...	1·74

By applying the shadow test, and proceeding by trial and error, the refractive index of the mineral may be found with a close approach to accuracy if the fragment is immersed successively in liquids more and more closely approximating to that of itself. The observations should be made with a low power objective in a room having a temperature of about 60°F.

It will be seen in some cases, that instead of resulting in a definite shadow, insertion of the finger produces colour fringes; these always indicate a close approximation between the values of mineral and liquid. They result from the fact that the liquid has much the stronger dispersion. In difficult cases, it is advisable to perform the experiment by the light of a sodium flame instead of in daylight.

Argillaceous Rocks. — Slates and shales are usually so fine-grained that even the microscope fails to reveal much as to their mineral composition. Some examples, however, seem to show that their constituents are similar to those of arenaceous rocks, the fragments merely having been ground down to much smaller dimensions. Crystals of pyrite, of fairly large size in some instances, cannot be regarded as derived fragments; they must have acquired their present characters as a result of changes since deposition of the sediment.

Calcareous Rocks.—As a rule, these are the result of accumulation of fragments of organic origin, although some of them, such as stalactite and travertine, are formed simply by deposition

from solution.   Oolitic limestones are probably
also inorganic in origin, the calcium carbonate of
the oolite having been deposited in successive
layers around a nucleus.   Calcite makes up the
bulk of such rocks and may easily be recognised as
such by the twinkling effect observed when the sec-
tion is examined over a rotated polariser, and by
the absence of crystal form.   The organisms of
which the rocks may be largely built are often
clearly recognisable.   Foraminifera such as
Globigerina, Nummulites, also various corals and
crinoids, are important limestone builders.

Some calcareous rocks consist entirely of
dolomite, a mass of mutually interfering rhomb-
shaped crystals, some of which may be sufficiently
well-formed to give material assistance in identifi-
cation.   Such rocks were originally ordinary lime-
stones; they have since been bathed in water
containing magnesium salts and have suffered
metasomasis.   All stages of the change may be
observed, some oolitic limestones showing per-
fectly formed rhombs of dolomite.   The tendency
is towards destruction of organic structures, but
there are some cases where oolites are still visible
even though the process of dolomitisation is com-
plete.   Other dolomitic limestones, not pure
dolomites, were probably deposited as the mixed
carbonates from the waters of desert areas.   In
some examples there has been re-sorting of the
two carbonates as a result of the work of under-
ground waters; this has given rise to the existence
of concretionary structures.   So far, the micro-

scope has not added greatly to our knowledge of such rocks.

Siliceous Rocks.—In some examples the material accumulated as a deposit of the remains of organisms with siliceous skeletons, sometimes sufficiently well-preserved to be identified. The most common are radiolaria and sponges, and the rock is known as chert. Good examples of beds of sponge chert are to be seen forming part of the Lower Greensand of Surrey, notably at Leith Hill and Tilburstow Hill. In other cases, as in flint, the rock is a silicified limestone, having resulted in consequence of the process of metasomatic replacement. Sometimes oolitic limestone has been silicified without destruction of the texture.

Carbonaceous Rocks.—A few of the Carboniferous coals exhibit the remains of spores and spore cases of the plants of that period. Other plant tissues are occasionally revealed by this method of investigation.

The distinction between sedimentary and igneous rocks, as seen under the microscope, is not always easy. The two classes overlap as tuffs, which are volcanic in origin, but are formed as a consequence of sedimentation; they may include fossils and are bedded. It must be borne in mind that the material of volcanic origin may form the whole of the sediment or it may be a very small percentage of the whole. Moreover, material originally volcanic in origin may be obtained second-hand if the area being denuded to supply the sediment is made of igneous rocks. True

bedding is exhibited by such rocks; but flow structure of some lavas, notably rhyolites, simulates bedding very closely in some instances.

METAMORPHIC ROCKS.—When an intrusive magma is injected into pre-existing rocks, heat is supplied to these, and under the new conditions thus established, re-arrangement of mineral constituents takes place. A siliceous sandstone becomes a quartzite, a shale or slate develops crystalline minerals like andalusite or chiastolite, a limestone becomes a marble, a dolomitic limestone with some siliceous content becomes a crystalline limestone containing silicates like forsterite, tremolite, and diopside; all of these may thus be produced in consequence of re-arrangement of materials proper to the country rock, and it may not be necessary to look upon the intrusive magma as being an active agent in any way except in so far as it supplies heat and thus establishes new conditions in the surrounding aureole. Obviously the formation of new minerals in such an aureole necessitates migration of mineral constituents within it to feed the growing crystals; it may be looked upon as a sort of domestic redistribution.

Earlier igneous rocks forming part of this aureole do not escape metamorphism; some of the minerals crystallised at comparatively low temperatures, and therefore are almost certain to become converted into others more in harmony with the new conditions established in consequence of the intrusion. Low temperature minerals become converted to others proper to the higher tempera-

tures, although in some cases, for example, the high temperature augite changes to low temperature hornblende by a sort of deferred igneous action where the original cooling was too rapid to permit the appropriate adjustment. Moreover, decomposed igneous rocks consist partly of minerals formed under atmospheric conditions; these certainly will be unstable at the higher temperatures established by the intrusion.

By this contact metamorphism, on the whole, the new minerals produced are those stable at high temperatures, and it might be expected that the subsequent cooling that must, of course, have taken place before the rocks come to be exposed at the earth's surface, would result in a reversal of the metamorphic processes—that metamorphic minerals formed at high temperatures could not possibly be made available for our examination. Response to this subsequent cooling is, however, not usual, and the high temperature minerals tend to remain without modification. There are some cases, however, in which there is a reversal, and the mineral deteriorates to a low temperature form. This is known as retrograde metamorphism.

A metamorphic aureole often surrounds a granitic mass which has a roughly circular outline, and it is easy to trace the junction between the intrusion and the country rocks. But many intrusions have a complicated shape because they have been injected along the stratification planes of bedded rocks in lit-par-lit fashion in such an intimate manner that an ordinary hand-specimen

may include several layers of the two kinds of
rock. In such a case we may expect the whole of
the sedimentary material, since no part of it is far
from the magma, to be metamorphosed. This
complicated intrusion may have affected a large
area of country, and what may be called the meta-
morphic aureole is not a mere fringe surrounding
a well-defined igneous mass. Contact metamor-
phism may then be indistinguishable from regional
metamorphism.

But we have seen that, at any rate in some cases,
the matter is not nearly so simple. Not only heat,
but material substance is sometimes, perhaps
always, transferred from intrusion to country rock ;
replacements are effected, and we are concerned
with metasomatic action superimposed upon that
resulting merely from the transfer of heat. More-
over, the transfused material is certainly hot, and
may itself be the main heating agent. There is
thus no guarantee, in fact there is no reason to
expect, that the country rock retains its original
bulk composition ; we are bound to consider the
probability that the new minerals of the aureole
contain mineral matter imported from the igneous
intrusion.

Now exudations from a granitic magma cer-
tainly consist of its residual liquid, the " ichor "
of Sederholm, and this effects metasomatism of
country rocks of varied kinds, late granitic
minerals being introduced, and the original con-
stituents being driven out to make room for them.
We thus picture the granitic intrusion as being
surrounded by a halo of a nature very similar to

itself, and beyond that one which has received the constituents displaced by the metasomatic action. It thus appears that new granite has been produced in consequence of a process of replacement; the granitic magma has grown by permeation. Country rocks of different characters are permeable in different degrees and therefore, though a banded arrangement may be produced by lit-par-lit intrusion, it may also result as a consequence of differential permeation by the ichor. The resulting rock is the migmatite of Sederholm; it is due essentially to permeation, and the ichor is sometimes referred to as "migma." Dr. Harker and others have referred to the difficulty of visualising conditions under which magnesia metasomatism might take place, the difficulty being that the magnesia content of the ichor is insignificant, but if we picture this ichor making a place for itself by expelling magnesia, we can conceive of a wave of magnesia metasomatism in advance of granitisation. The difficulty seems to be overcome by this supposition.

It would be foolish to deny that granite does in some instances find a place for itself by pushing aside the rocks of earlier date, but at the greater depths this progress by permeation (granitisation) seems to be established as a fact. Granite, then, may be a sort of pseudomorph after the rock replaced. Banded structures of sedimentary rocks may be retained, even perhaps emphasised, as a result of selective permeation, and these gneisses thus retain evidence pointing to their mode of origin. The whole is a result of metamorphism

combined with metasomatism, and if we regard the migma as being the important purveyor of heat, the distinction between the two processes disappears.

It is conceivable that migmatisation might proceed so far that all the layers are metasomatised; the whole rock then becomes a granite, and it has been manufactured as a result of conversion of a rock originally, perhaps, sedimentary; it is an example of ultrametamorphism. On this hypothesis, it thus appears that any metamorphic rock represents merely a stage in a series of operations which, if they had been continued to the limit, would have resulted in the manufacture of a rock not to be distinguished from one of igneous origin. It may be that we shall be compelled to regard this alkali metasomatism or granitisation as being something much bigger than a mere incident taking place in advance of a granitic intrusion. There may be a continuous uprise from some sub-crustal material, passing up into the earth's crust, affecting rocks some miles in thickness, and liable to cause the mobilisation of rocks of very varied nature.

Regional metamorphism is by some considered to be synonymous with dynamic metamorphism, and it is established that in certain cases dynamic action is responsible for certain mineral changes. Obviously, heat must result from earth movements, and new minerals, crystallised under directed pressure, are produced. It is probable, however, that at any rate under near-surface conditions, the result is destructive rather than con-

structive; at greater depths conditions are probably more favourable for recrystallisation. If, however, earth movements are responsible for large-scale metamorphism, then the most striking results should be associated with intense folding. But the fact is that the most striking metamorphic effects are exhibited by strata that still lie approximately horizontal; earth movements in themselves cannot be regarded as the prime cause of regional metamorphism.

Metamorphism may be a consequence of subsidence. Admittedly, certain areas have been depressed during long periods, sedimentation having taken place meanwhile to such an extent that the thickness of the deposits amounts to some miles. The earlier deposits of such a series have undoubtedly been carried down to regions where temperatures were high, and metamorphism by heating may justifiably be expected, the degree of metamorphism being greatest in the lower strata and diminishing in an upward direction. By some workers this is taken as axiomatic, and cases where more and less metamorphosed strata alternate, so that in places a more metamorphosed layer rests upon one less affected, subsequent inversion has been deduced. Professor Read contends, however, that there is no necessity to postulate such inversion. He cites examples of strata that have undoubtedly been buried under a thick cover without having undergone any metamorphic changes; and he therefore advocates metamorphism by permeation; the essential condition, in his opinion, is not thickness of cover,

but power to admit the hot gases to which meta-
morphism is due.

Some Examples of Metamorphic Rocks.

Schist.—Many metamorphic rocks are characterised by
approximate parallelism of the crystalline minerals con-
stituting them.   This may be due to preservation of
original bedding, the alternating layers thus owing their
existence to the structure of the original rock; the minerals
developing on any particular horizon will, in the absence
of introduced material foreign to the parent rock, have
been fed by the constituents already in place, the changes
being due to the operation of heat.   Even if metasomatism
has been effective, some of the original material may be
expected to remain, and thus to have an influence on the
nature of the minerals composing the new band.   Growth
of any new mineral may be expected to take place most
easily along the layers which contain the materials neces-
sary for its sustenance, and hence crystal elongation tends
to be along the direction of the original bedding.

On the other hand, one kind of slaty cleavage is
developed, usually in argillaceous rocks, as a result of
lateral pressure effecting a re-arrangement of minute flaky
particles, these taking up a position perpendicular to the
direction in which the pressure operated; the cleavage is
thus independent of bedding.   As new micaceous minerals
may be developed in these slates, lying along the planes
of cleavage of the rock, they must be attributed to the
pressure, assisted perhaps by heat.   Where these new
micaceous minerals are more prominent than in normal
slates, the rock is known as a phyllite.   There thus comes
into existence a layered rock, the structure of which is a
new one, and a schist may perhaps be regarded as an
extreme case of a phyllite.

The two conceptions are thus definitely opposed, but in
either case a schist may be regarded as a layered crystal-
line rock, in which adjacent layers are, as far as naked
eye observation is concerned, identical.   The name of some
prominent mineral is usually prefixed to describe the rock,
as, for example, mica, hornblende, glaucophane, quartz,
chlorite, or andalusite.   Any one of these minerals may be
taken to indicate only moderately high temperatures.

Gneiss.—This is another example of a crystalline rock in
which the constituent minerals are arranged in more or
less parallel layers, but here the foliation is usually obvi-

ous in a hand-specimen, adjacent layers having essentially differing composition. Again the foliation may be a relic of bedding, but, formed at higher temperatures than schist, each growing crystal had a greater sphere of influence: hence the coarser structure. Alkali felspars are more conspicuous than they are in schists, perhaps because they are more stable than muscovite at higher temperatures. It is probable that metasomatising fluids have been responsible for the introduction of appreciable quantities of outside material.

It is possible that the foliation is due to earth movements. If pressure in one direction is greater than it is in others, the tendency will be for expansion perpendicular to this line, shearing will result, and foliation will develop along the directions of yielding; a rock with porphyritic felspars, will acquire an eyed (augen) structure in consequence of a process which is largely destructive in its action. It seems probable that the augen will become smaller under more severe pressure. Such a rock, derived from one of igneous origin, is known as orthogneiss; a gneiss derived from a sedimentary rock is a paragneiss. A composite gneiss results from lit-par-lit injection.

Granulite may perhaps be regarded as a variety of gneiss. Its foliation is not conspicuous, largely because of the scarcity or absence of micas. The constituent minerals, felspars, quartz, with perhaps pyroxene, garnet, or kyanite, usually occur as interlocking grains without marked elongation.

Hornfels.—This is a rock not showing parallel arrangement of the constituent minerals, probably produced as a result of contact metamorphism of an argillaceous rock. The recrystallisation, not under directed pressure, has tended to eliminate original bedding or cleavage. Quartz, micas, and felspars are present, with perhaps aluminous minerals like andalusite or cordierite.

Crystalline Limestone.—When pure, this yields an aggregate of calcite grains. In presence of silica, however, a lime pyroxene (wollastonite) is formed, and carbon dioxide is expelled. If aluminous impurities are present in addition, minerals like lime garnet are produced. Dolomitic limestones suffer dissociation of the magnesian part with greater ease than in the case of the calcic part, and in the presence of silica, forsterite is a common product. At higher temperatures, lime-magnesia silicates are produced, represented by diopside and tremolite. This process of reconstruction of dolomite is known as dedolomitisation.

Chiastolite Slate.—If slaty cleavage is to be regarded as having been produced as an act of metamorphism, this rock has suffered two metamorphic processes, because the chiastolite is undoubtedly due to contact metamorphism at a later date. The only recognisable crystals are those giving the name to the rock.   Such double metamorphism must have affected many other rocks, but the accurate working out of their history is a matter of considerable difficulty.

The history of petrological study is not a record of steady progress in a given direction ; opinions have oscillated, now in one direction, now in the other, and it would be presumptuous to attempt a forecast of the trend of opinion in the next generation.   One can only preach what one believes to be the gospel, and then leave matters in the hands of those who are still young in spirit as well as in years.

SUGGESTIONS FOR FURTHER READING.

N. L. Bowen.—The Evolution of the Igneous Rocks. Humphrey Milford, 1928.

R. A. Daly.—Igneous Rocks & their Origin. McGraw-Hill Co., 1914.

A. Harker.—Petrology for Students. Camb. Univ. Press.
——— The Natural History of Igneous Rocks. Methuen, 1909.
——— Metamorphism. Methuen, 1932.

F. H. Hatch & A. K. Wells.—The Petrology of the Igneous Rocks. Allen & Unwin, 1936.

A. Holmes.—The Nomenclature of Petrology. Murby & Co., 1928. (Out of print, New Edition in preparation.)

A. Johannsen.—A Descriptive Petrography of the Igneous Rocks. Camb. Univ. Press. Vol. I. 1931. Vol. II. 1932.

H. H. Read.—Metamorphism and Igneous Action. Address to Section C, British Association, 1939.

S. J. Shand.—Eruptive Rocks. Murby & Co., 1927.

J. J. H. Teall.—British Petrography. Dulau, 1888.

N. H. & A. N. Winchell.—Elements of Optical Mineralogy. Chapman & Hall. Part I., 1922. Part II., 1927. Part III., 1929.

INDEX

A LIST OF THIN SECTIONS

SPECIALLY PREPARED TO ILLUSTRATE

H. G. Smith's "MINERALS AND THE MICROSCOPE."

SECTIONS OF SELECTED
UNIAXIAL AND BIAXIAL MINERALS.

Cut in appropriate directions to give interference figures. Also selections to illustrate refractive index, polarisation, and extinction.

ORDINARY LIGHT.

   1. Three minerals mounted together to show difference of refractive index (*Quartz, Fluor, Topaz*) **3/0**

PARALLEL POLARISED LIGHT.

   2. Straight extinction (*small quartz crystals*) **1/6**
   3. Oblique extinction (*cleavage flake of Gypsum*) **1/6**

INTERFERENCE FIGURES.

   4. Uniaxial +(*Quartz*) **3/0**
   5.   ,,   −(*Tourmaline*) **3/0**
   6. Biaxial +(*Topaz*) **3/0**
   7.   ,,   −(*Muscovite*) **2/0**

SPECIAL INTERFERENCE FIGURES.

   8. Smaller optic axial angle (*Aragonite*) **3/0**
   9. Partial biaxial (*Epidote*) **3/0**
  10. Pseudo-uniaxial (*Phlogopite*) **2/0**

EFFECTS OF VARYING THICKNESSES.

  11. Biaxial (*Muscovite*) **3/0**
  12. Pseudo-uniaxial (*Phlogopite*) **3/0**

      Collection of 12 slides, listed above, **30s.**

    TO SHOW NEWTON'S SCALE AND FOR DETERMINATION OF
        SIGN : *Wedge of Quartz* .... From **17s. 6d.** upwards

    FOR DETERMINATION OF SIGN : *Mica plate* **4/0**

        All prices are subject to fluctuation.

  * *When ordering a quartz wedge or mica plate please give size of slot in the microscope for which it is required.*

COLLECTION OF

150 THIN SECTIONS OF ROCKS.

This set of 150 thin sections constitutes a carefully selected and representative collection of rock types.

It includes the 53 thin sections (indicated by asterisks) originally selected for students using " Minerals and the Microscope," by H. G. SMITH.

Price 3s. 6d. per slide.

IGNEOUS ROCKS.

1 *Microcline granite, *Rubislaw Quarries, Aberdeen.*

2 Biotite granite (Adamellite), *Shap, Westmorland.*

3 *Biotite granite, *Cheesewring Hill, Cornwall.*

4 Leinster granite, *Killiney, Co. Dublin.*

5 Coarse Leinster granite, *Three Rock Mt., Co. Dublin.*

6 Tourmaline granite, *Troon, Cornwall.*

7 *Tourmaline granite (Luxullianite), *Luxulyan, Cornwall.*

8 *Biotite - hornblende - granite, *Dalbeattie, Scotland.*

9 Augite granite, *Boosberg, Vosges, France.*

10 Basic secretion in granite, *Shap, Westmorland.*

11 Greisen, *Grainsgill, Cumberland.*

12 Pegmatite, *W. of Cripple Creek, Colorado.*

13 Augite syenite (Laurvigite), *Laurvig, Norway.*

14 Nepheline syenite (Foyaite), *Sierra de Monchique, Portugal.*

15 Nepheline syenite (Ditroite), *Ditro, Transylvania.*

16 *Hornblende syenite, *Plauen'scher Grund, Dresden.*

17 *Augite syenite (Olivine monzonite), *Kentallen, Scotland.*

18 Monzonite, *Monzoni, Tyrol.*

19 Quartz-enstatite-diorite, *Penmaenmawr, Wales.*

20 Diorite, *Vosges, France.*

21 Quartz diorite, *St. Sampson's, Guernsey.*

22 *Hornblende-biotite-diorite, *Guernsey.*

23 Troctolite, *Coverack, Cornwall.*

24 Anorthosite, *Lewis, Essex Co., New York.*

25 Essexite, *Lennoxtown, Glasgow.*

26 Norite, *Auchenbradie Quarry, Aberdeen.*

27 Kimberlite, *Murfreeshoro, Arkansas, U.S.A.*

28 Teschenite, *Inchcolm, Firth of Forth.*

29 *Dunite, *Mt. Dun, New Zealand.*

30 Lherzolite, *Arguenos, France.*

31 Cortlandtite, *Syracuse, New York.*

32 Pyroxenite (Bronzitite), *N. Carolina, U.S.A.*

33 *Augite picrite, *Inchcolm, Firth of Forth.*

34 *Serpentine, *Banff, Scotland.*

35 *Hypersthene gabbro (Hyperite), *Maud Junction, Aberdeen.*

36 *Gabbro, *Carrock Fell, Cumberland.*

37 Hypersthene gabbro, *St. Sampson's, Guernsey.*

38 Saussuritic gabbro, *Lendalfoot, Ayrshire.*

39 *Granophyre, *Mourne Mts., Ireland.*

40 Augite granophyre, *Carrock Fell, Cumberland.*

41 *Riebeckite eurite, *Ailsa Craig, Firth of Clyde.*

42 *Aplite, *Long Downs, Falmouth, Cornwall.*

43 Aplite, *Ennerdale, Cumberland.*

44 Spodumene-bearing elvan, *Co Dublin.*

45 Mylonised elvan, *Co. Dublin.*

46 *Quartz porphyry, *Armboth Dyke, Thirlemere, Cumberland.*

47 Quartz porphyry, *Vosges, France.*

48 Quartz felsite, *St. John's Vale, Cumberland.*

49 Orthophyre, *Mid-Eildons, Nr. Melrose, Scotland.*

50 Keratophyre, *Ruabon, Wales.*

51 Porphyrite, *Eycott Hill, Cumberland.*

---

52 Andesite porphyry, *Newton, Mass., U.S.A.*

53 *Hornblende porphyrite, *Colvend, Dalbeattie.*

54 Bostonite, *Essex Co., New York.*

55 Solvsbergite, *Solvsberget, Norway.*

56 *Dolerite, *Clee Hill, Ludlow.*

57 *Dolerite, *Craiglochart, Edinburgh.*

58 Dolerite, *Pouk Hill, Walsall.*

59 Nepheline dolerite (Nephelinite), *Lobau, Saxony.*

60 Tachylytic edge of dolerite sill, *Dippin, Arran.*

61 Diabase (Gimlet Rock), *Pwllheli, Wales.*

62 Lugarite, *Lugar, Ayrshire.*

63 Mica-lamprophyre (Minette), *Sale Fell, Cumberland.*

64 Mica - lamprophyre (Minette), *Franklin Furnace, New Jersey, U.S.A.*

65 Limburgite, *Limburg, Kaisertuhl.*

66 Alnoite (Melilite basalt), *Spiegel River Valley, Cape Colony.*

67 Vogesite, *Glen Catacol, Arran.*

68 Vogesite, *Andlautal, Vosges Mts.*

69 *Eclogite, *Eppenreuth, Bavaria.*

70 *Spherulitic obsidian, *Isle of Lipari, Sicily.*

71 Obsidian, *Millard Co., Utah.*

72 *Pitchstone with microliths, *Corriegills, Arran.*

73 Porphyritic pitchstone, *Corriegills, Arran.*

74 Pumice, *Millard Co., Utah, U.S.A.*

75 Rhyolite (Lea Rock), *Wellington, Salop.*

76 Spherulitic rhyolite, *Cloughmore, Co. Antrim.*

77 *Spherulitic rhyolite, *Long Sleddale, Cumberland.*

78 Rhyolite showing fluidal structure, *Ballymena, Co. Antrim.*

79 Trachyte, *San Leonardo, Etna.*

80 Augite trachyte, *Peppercraig Hills, Haddington, Scotland.*

81 *Trachyte with sanidine, *Drachenfels, Siebengebirge.*

82 *Hypersthene andesite, *Dumyat, Stirling.*

83 Biotite andesite, *Craigowerhouse, Auchtermuchty, Fife.*

84 Hornblende andesite, *Glen Coe Pass, Argyllshire.*

85 *Hornblende andesite, *Monarch, Chaffee Co., Colorado, U.S.A.*

86 *Hornblende andesite, *Mt. Shasta, California.*

87 *Hornblende andesite, *Wolkenberg, The Rhine.*

88 Dacite, *Chemnitz, Saxony.*

89 Glassy Pantellerite, *Pantellaria.*

90 Glassy basalt, *Darmstadt, Germany.*

91 *Porphyritic olivine basalt, *Arthur's Seat, Edinburgh.*

92 Amygdaloidal basalt, *High Tor, Matlock.*

93 Phonolite, *Beacon Hill, Cripple Creek, Colorado.*

94 *Nosean phonolite, *Wolf Rock, Cornwall.*

95 *Leucite tephrite with hauyne, *Tavolato, Rome.*

96 *Leucitophyre, *Rieden, Eifel.*

97 Epidosite, *Stornoway, Lewis, Scotland.*

98 Melaphyre, *Vosges, France.*

99 Kenyte, *Cape Royds, Ross Island. Antarctic.*

100 Palagonite, *Tan-y-Craig, Wales.*

101 Spilite (Pillow lava), *Mullion Island, The Lizard, Cornwall.*

102 Volcanic agglomerate, *Arthur's Seat, Edinburgh.*

103 *Calcareous tuff, *Goblin Combe, Weston-super-Mare.*

104 Volcanic Ash, *Lion's Haunch, Arthur's Seat, Edinburgh.*

METAMORPHIC ROCKS.

105 *Mica-schist with garnet, *Pitlochry, Perthshire.*

106 Mica-schist with tourmaline, *Ballycomus, Co. Antrim, Ireland.*

107 Graphite - mica-schist, *McDowell Co., North Carolina, U.S.A.*

108 Talc schist, *St. Lawrence Co., New York, U.S.A.*

109 *Chlorite schist, *W. of Portsoy, Banff, Scotland.*

110 Andalusite schist, *Killiney, Co. Dublin.*

111 *Actinolite schist, *Garron Point, Banff.*

112 Hornblende schist, *Tregurthey, Cornwall.*

113 *Glaucophane schist, *Nocchic, Sussial, Italy.*

114 *Cordierite - andalusite - gneiss, *Schinckoppe, Riesengebirge.*

115 Sillimanite - garnet - gneiss, *Nr. Hague, Warren Co., New York.*

116 *Kyanite granulite, *Rohrsdorf, Saxony.*

117 Hornstone, *Charnwood Forest, Leicester.*

118 *Ottrelite slate, *Ottré, Belgium.*

119 *Chiastolite slate, *Shiddaw, Cumberland.*

120 Clay Slate, *Penrhyn Quarries, Nr Bangor, Wales.*

---

121 Clay Slate, *Ballachulish, Argyll-shire, Scotland.*
122 Mylonite (crushed slate), *Balmacara, Skye.*
123 *Crystalline limestone, *Carrara, Italy.*
124 Garnetiferous greenstone, *Cambourne, Cornwall.*

125 Greenstone with axinite, *Carrickdu, St. Ives, Cornwall.*
126 Epidiorite, *Kennack, Cornwall.*
127 Epidote - bearing rock, *Shap, Westmorland.*

SEDIMENTARY ROCKS.

128 *Normal quartzite, *Hartshill, Nuneaton, Warwickshire.*
129 Torridon sandstone, *Assynt, Sutherland.*
130 *Permian Sandstone, *Grange Hill, West Kirby, Cheshire.*
131 Glauconite sandstone, *Hollybush Hill, Malvern.*
132 *Glauconite sandstone, *Upper Greensand, Swanage, Dorset.*
133 Keuper sandstone, *Basement beds, Nr. Liverpool.*
134 Millstone Grit, *Dunford Bridge, Yorkshire.*
135 *Ferruginous sandstone, *Portland, Conn., U.S.A.*
136 Barytiferous sandstone, *Tegg's Nose, Nr. Macclesfield, Cheshire.*
137 Ganister sandstone, *Lower Coal Measures, Bolton, Lancs.*
138 Serpula limestone, *Upper Greensand, Worbarrow Bay, Dorset.*

139 *Foraminiferal limestone, *Castleton, Derbyshire.*
140 *Nummulitic limestone, *The Pyramids, Ghizeh, Egypt.*
141 *Globigerinal limestone, *Athenion, Cyprus.*
142 Pisolitic limestone, *Colwell Copse, Malvern Hills.*
143 *Oolite, *Upper Portland Beds, Bath.*
144 *Normal Chalk, *Portrush.*
145 *Dolomite, *Lummaton Quarry, Torquay.*
146 Dolomite, *Little Falls, New York.*
147* Silicified oolite, *Stale College, Penn., U.S.A.*
148 Bryozoa Limestone, *Portishead, near Bristol.*
149 Oolitic ironstones, *Low Main Coal, Derbyshire.*
150 Banded chert, *Upper Greensand, Great Haldon, Devon.*

THIN SECTIONS OF MINERALS.

In the following series each slide, as far as possible, contains only one mineral.

Price: **2s. 9d.** per slide except when otherwise indicated.

1	Actinolite	18	Cassiterite
2	Agate	19	Chalcedony
3	Albite, 3s. 6d.	20	Corundum, 5s.
4	Analcite	21	Diallage
5	Andalusite	22	Dolomite
6	Anhydrite	23	Elæolite
7	Anorthite	24	Enstatite
8	Apatite	25	Epidote
9	Aragonite	26	Flint
10	Arfvedsonite, 3s. 6d.	27	Fluorite
11	Augite	28	Garnet (Almandine)
12	Axinite	29	Gypsum
13	Barytes	30	Hornblende
14	Beryl, 4s.	31	Hypersthene
15	Bronzite	32	Jade (Nephrite), 4s.
16	Bytownite	33	Jasper
17	Calcite		

34 Labradorite
35 Microcline
36 Microperthite
37 Oligoclase
38 Olivine
39 Opal, Common
40 Opal, Precious, 4s.
41 Orthoclase
42 Perthite
43 Quartz
44 Siderite
45 Sodalite
46 Talc
47 Tourmaline
48 Tremolite, 4s.
49 Wollastonite
50 Zircon, 5s. 6d.